# APPLICATION OF THE GAUSSIAN MODEL TO A PARTICULATE EMISSION CONTROL STRATEGY EVALUATION PROBLEM

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## ABSTRACT

The Gaussian model for a continuous point source is presented. This model was applied to a control strategy evaluation project for the Weyerhaeuser - Pine Bluff, Arkansas mill for the preliminary assessment of particulate emission control techniques. The results show that the slaker stack may be an exceptionally strong source of downwind particulates leading to substantial violations of the Arkansas ambient standard. However, there are indications that these results may be in error due to non-negligible settling velocities for the slaker stack particulates. Assuming that the concentration of particulates from the slaker stack is actually small, the results indicate that only the use of a wet scrubber on the recovery boiler stack at an emission rate of 22.8 g/sec is unacceptable. All other control techniques lead to acceptable off-plantsite particulate concentrations. This project was conducted under the assumption of a constant wind speed throughout the mixing layer.

To evaluate the effects of an increase in wind speed with height, the Pine Bluff results were reevaluated assuming a power law wind speed profile with exponents ranging from 0.25 to 0.50. The results indicate that an increase in wind speed with height leads to lower concentrations at large downwind distances ($x \geq 2$ km) than predicted under a constant wind speed assumption. This implies that the origional Pine Bluff results are conservative.

# Chapter I

## INTRODUCTION

As a result of the requirements of state and federal regulatory agencies and the increasing number of pollutant control techniques, many companies have found it necessary to use computer programs to estimate the impact of pollutant emissions on the environment. The programs most often used for this purpose have been based on the Gaussian model. Several of the more popular Gaussian model programs (UNAMAP series) may be obtained from the National Technical Information Service (NTIS). Because of their simplicity and ease of use, these programs offer very convenient methods for the initial assessment of various control techniques prior to the use of more elaborate models for definitive impact estimates.

During the summer of 1976, corporate engineers of the Weyerhaeuser Company initiated a process which should lead to the procurement of new particulate emission source permits for the recovery and bark boiler (hog fuel boiler) units of their Pine Bluff, Arkansas mill. The Arkansas Department of Pollution Control and Ecology (ADPCE) has set an ambient standard for particulates at 150 $\mu g/m^3$ averaged over a thirty minute period, not to be exceeded more than once per year at locations outside of plantsite boundaries. Arkansas authorities require that preliminary concentration estimates be made by computer modeling for proposed sources.

Source parameters were obtained from plant engineers for the proposed control techniques on the mill's recovery and bark boiler stacks. These techniques and associated source parameters are further discussed in Chapter III. Using the source parameters and the UNAMAP program PTMTP, the control techniques were evaluated.

The purpose of this thesis is threefold. First, the use of Gaussian modeling techniques in industrial control strategy evaluation (ICSE) will be discussed. Second, the model implementation in the project mentioned above will be discussed. Finally, an evaluation of how the wind speed profile may affect the results will be presented.

# Chapter II

## THE GAUSSIAN MODEL AND ITS USE IN CONTROL STRATEGY EVALUATIONS

Prior to a detailed discussion of the Gaussian model and its use, a few comments on models in general are useful. The selection of the most suitable model is critical in ICSE. It is the purpose of these preliminary comments to present some of the considerations which must be made in the process of selecting a model.

The basic goal of the atmospheric pollution modeler is to realistically describe receptor concentrations. In selecting the appropriate model, the following requirements should be satisfied:

1. The model should be appropriate for the source-to-receptor distances.
2. The model should satisfy the spatial and temporal requirements of the problem.
3. The model should simulate the effects of terrain features, chemical reactions, meteorology, and emission characteristics on pollutant concentrations.
4. The model should exhibit the effects of particle sedimentation.
5. The model should be capable of indicating the relative contributions from each source at the receptor sites. This requirement is very important in ICSE.

In the atmosphere, pollutant dispersion is due predominately to turbulent diffusion. There are two fundamental ways of describing this process, the Eulerian and Lagrangian approaches. The Eulerian approach describes the behavior of a pollutant species relative to a fixed coordinate system, while the Lagrangian approach describes pollutant concentrations while following air parcels.

The governing equation for the mean species concentration under the Lagrangian approach is given (Seinfeld, 1975) as:

$$\langle c(X, t)\rangle = \int_{\substack{\text{All}\\\text{Space}}} Q(X, t|X_0, t_0)\langle c(X_0, t_0)\rangle dX_0 + \int_{\substack{\text{All}\\\text{Space}}}\int_{t_0}^{t} Q(X, t|X', t')S(X', t')dt'dX' \tag{1}$$

where c is the species concentration, X is a position vector, t is time, $Q(X, t|X_0, t_0)$ is the transition probability density for movement from location $X_0$ at time $t_0$ to location X at time t, $S(X', t')$ is the species emission rate at location X' and time t', and brackets $\langle\rangle$ denote a time averaged quantity. Eq. 1 is valid only for inert pollutants. The transition probability density Q takes into account the effects of advection (horizontal transport of pollutants due to the wind) and turbulent diffusion. The difficulty of using this approach lies in determing the form of Q.

If a pollutant is assumed to be inert, and the turbulence is assumed to be stationary and homogeneous, the solution to Eq. 1 yields the Gaussian model. The form of the Gaussian model depends upon the type of sources being considered, i.e., point, line or area sources, and further depends upon the continuity of the pollutant emission. In the present study only continuous point sources were considered.

Only this type of model is discussed here. Turner (1970), Perkins (1974), and Seinfeld (1975) discuss the other forms of the Gaussian model.

A coordinate system is chosen such that x is in the horizontal direction of the mean wind velocity, z is in the vertical direction, and y is in the horizontal crosswind direction. The Gaussian model equation for the mean concentration of a species in a plume is given (Turner, 1970 and Seinfeld, 1975) as:

$$\langle c(x,\ y,\ z)\rangle = \frac{S}{2\pi\sigma_y\sigma_z U}\left(\exp\left[-\frac{1}{2}\left(\frac{Y}{\sigma_y}\right)^2\right]\right)\left(\exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right]\right.$$
$$+\exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right]+\sum_{n=1}^{\infty}\left\{\exp\left[-\frac{1}{2}\left(\frac{Z-H-2nL}{\sigma_z}\right)^2\right]\right.$$
$$+\exp\left[-\frac{1}{2}\left(\frac{Z+H-2nL}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{Z-H+2nL}{\sigma_z}\right)^2\right]$$
$$\left.\left.+\exp\left[-\frac{1}{2}\left(\frac{Z+H+2nL}{\sigma_z}\right)^2\right]\right\}\right) \qquad (2)$$

where S is the source emission rate, $\sigma_y$ and $\sigma_z$ are the standard deviation distances of the plume concentration distribution in the crosswind and vertical directions, U is the mean wind speed, H is the height of the plume centerline above the ground level, and L is the inversion height (mixing depth). Two assumptions are inherent to Eq. 2 (Seinfeld, 1975). First, turbulent diffusion in the direction of the mean wind velocity is assumed to be small compared with advection. Second, the ground is assumed to act as a perfect reflector of the pollutant; the particle deposition at the ground is not considered. Turner (1970) states that the Gaussian model is adequate for particles smaller than 20 microns in diameter. The simple Gaussian model has the following advantages:

1. It may be applied separately for each source to give the pollutant contributions at each receptor site. These "partial" concentrations are summed to give the total mean concentration at each receptor.
2. It requires the use of two dispersion parameters which have been empirically determined by several researchers under various meteorological conditions.
3. It does not require the use of sophisticated numerical techniques employed by some models. Thus, computer time and space and computational stability do not become problems in its use.

These advantages make the Gaussian model desirable for many modeling projects.

The modeler must realize that the Gaussian model is approximately accurate for a restricted set of area and meteorological conditions. The value of U used in the model is usually assumed to be constant throughout the modeled mixing layer. The validity of this assumption is controlled by both terrain and meteorological conditions. One would expect this assumption and that of homogeneous turbulence to hold only above relatively flat terrain. Meteorological conditions are not constant in time. Thus, one cannot expect the value of U or the level of turbulence to remain constant over long time periods.

This means that the Gaussian model can only be used for receptor sites relatively close to the source.

The Gaussian model is limited in its ability to accurately predict pollutant concentrations. Turner (1970) states that the Gaussian model is accurate within a factor of three under the following conditions:

1. source-to-receptor distances up to a few hundred meters for all atmospheric stabilities.
2. source-to-receptor distances up to a few kilometers for neutral to moderately unstable conditions.
3. source-to-receptor distances up to ten kilometers or more for unstable conditons in the lower 1000 m of the atmosphere topped by a strong temperature inversion.

For all other conditions, the Gaussian model gives values which are generally within an order of magnitude of those observed. Generally, it should only be used for initial concentration estimates.

Equation 2 may be simplified if the mixing depth is sufficiently large. For large mixing depths, Eq. 2 reduces to:

$$\langle c(x,\ y,\ z)\rangle = \frac{S}{2\pi\sigma_y\sigma_z U}\left(\exp\left[-\frac{1}{2}\left(\frac{Y}{\sigma_y}\right)^2\right]\right)\left(\exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right]\right) \qquad (3)$$

To evaluate the importance of mixing depth considerations in ICSE, normalized pollutant concentrations $\tilde{C}$ ($\tilde{C} = U\langle c(x,\ o,\ o)\rangle /S$) were computed, both considering mixing depths ($\tilde{C}_I$) and neglecting mixing depths ($\tilde{C}_u'$). A mixing depth of 100 m under a Pasquill-Gifford stability class D (neutral atmospheric stability) was considered. Such a low mixing depth is not typically characteristic of stability class D conditions, but was selected here to give an example of an extremely poor condition. Plume heights were expressed in terms of fractional mixing depths R. Values of $\sigma_y$ and $\sigma_z$ were obtained from graphs presented by Turner (1970). The ratio of $\tilde{C}_I$ to $\tilde{C}_u'$ versus R is plotted for various downwind distances in Figure 1. From the graph it can be seen that the effect of the mixing depth on predicted concentrations increases with increasing $R (R < 1)$. This implies that concentrations from plumes just below the mixing lid will be underestimated in comparison to those from low plumes at a given distance from the source if inversion heights are ignored. From the graph, it can be seen that the influence of the mixing depth on predicted concentrations increases with downwind distance. However, it can also be seen that for a mixing depth of 100 m, the predicted difference between the values of $\tilde{C}_I$ and $\tilde{C}_u'$ is within the suggested accuracy of the Gaussian model up to a distance of 10 km. The agreement between the two sets of results improves with increasing mixing depth. This implies that only the effects of very small mixing depths need be considered via Eq. 2. For the remainder of the discussion in Chapter II, it will be assumed that the mixing depth is sufficiently large to warrant consideration of concentrations predicted by Eq. 3.

To insure the reliability of ICSE estimates, the values of the variables in Eq. 3 should be accurately determined for the conditions to be modeled. It is desirable to determine these variables with the

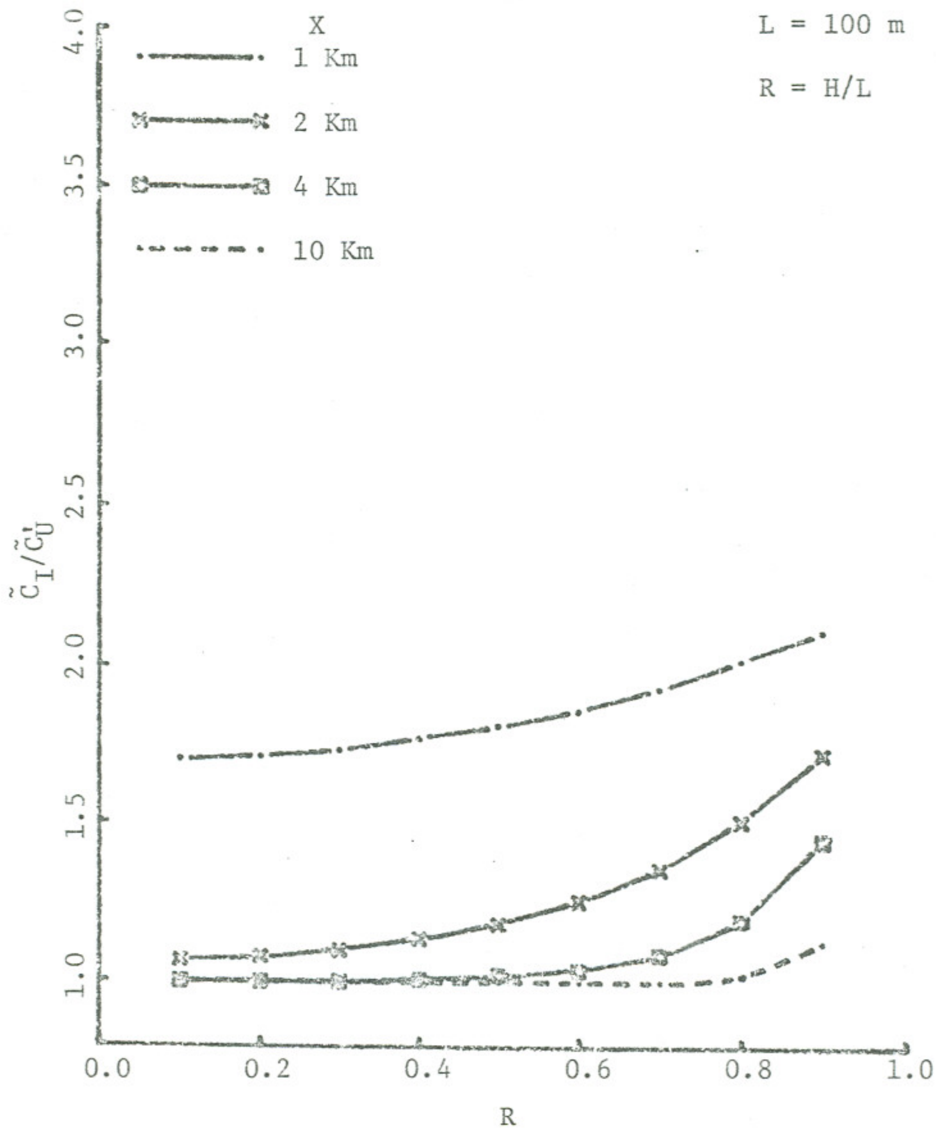


Figure 1. Ratio of normalized concentrations ( $\tilde{C}_I/\tilde{C}_U'$ ) versus the plume height ratio R.

same degree of accuracy for all sources. The modeler should strive to minimize the artifacts of the model.

First, consider the problem of estimating the plume height H. Previous studies have shown that H is determined by the gas exit temperature and velocity, the volume flow rate from the source, the wind speed, and the atmospheric stability. Numerous studies have been conducted to determine empirical formulas for the prediction of plume rise. Many of these studies and empirical formulas are discussed by Briggs (1969). Two empirical formulas have gained wide acceptance. Holland (Briggs, 1969) developed an empirical formula based on photographs of plumes within a few hundred meters of relatively cool sources. Briggs (1969, 1971, 1972) developed a set of semi-empirical formulas based on both theoretical considerations and observations made by researchers for a wide range of governing conditions and downwind distances. The Holland formula is given (Briggs, 1969 and Hesketh 1973) as:

$$\Delta H = F_A V_S D_S (1.5 + 2.83 \times 10^{-3} P_A (T_S - T_A) D_S / T_S) / U$$

$$F_A = 1.2, \text{ unstable atmospheric conditions}$$
$$= 1.0, \text{ neutral conditions}$$
$$= 0.8, \text{ stable conditions} \qquad (4)$$

where $\Delta H$ is the plume rise, $V_S$ is the gas exit velocity, $D_S$ is the inside stack diameter, $P_A$ is the ambient pressure, $T_S$ is the gas exit temperature, $T_A$ is the ambient temperature, and U is the mean wind speed. Researchers of the ADPCE prefer to use this formula above all others for short stacks and cool plumes (Bane, 1976). Briggs' formulas are given (Briggs, 1969, 1971, 1972) as:

$$F = gV_S D_S (T_S - T_A)/4T_S \tag{5}$$

where F is the buoyancy flux and g is the gravitational acceleration, and:

$$S_A = (g/T_A)\partial T_A/\partial Z \tag{6}$$

where $S_A$ is the atmospheric stability parameter. For unstable and neutral conditions:

$$x^* = 14F^{5/8}\ (\mathrm{m}),\ F < 55\mathrm{m}^4/\mathrm{sec}^3 \tag{7a}$$

$$= 34F^{2/5}\ (\mathrm{m}),\ F \geq 55\mathrm{m}^4/\mathrm{sec}^3 \tag{7b}$$

where x* is the distance at which the turbulent diffusion becomes the dominant parameter influencing plume rise:

$$x_m = 3.5x^* \tag{8}$$

where $x_m$ is the distance from the source to the point of maximum plume rise, and:

$$\Delta H = 1.6F^{1/3}U^{-1}x^{2/3},\ x < x_m \tag{9a}$$

$$= 1.6F^{1/3}U^{-1}x_m^{2/3},\ x \geq x_m\ . \tag{9b}$$

For stable conditions:

$$x_m = \pi U S_A^{-1/2} \tag{10}$$

$$\Delta H = 1.6F^{1/3}U^{-1}x^{2/3},\ x < x_m \tag{11a}$$

$$= 2.4(F/US_A)^{1/3},\ x \geq x_m. \tag{11b}$$

For low wind speeds and stable conditions:

$$\Delta H = \mathrm{Min}\begin{pmatrix} 2.4(F/US_A)^{1/3} \\ 5.0F^{1/4}S_A^{-3/8} \end{pmatrix},\ x \geq x_m. \tag{12}$$

To evaluate these plume rise determination methods, normalized ground level concentrations and plume heights were computed for a variety of gas exit temperatures and velocities. Parameters held constant during the computations were the atmospheric stability (class D), the ambient temperature (293°K), the ambient pressure (1000 mb), the stack height (50 m), and the inside stack diameter (1.0 m). Values of $\sigma_y$ and $\sigma_z$ were obtained from graphs presented by Turner (1970). The computed plume rise is plotted against the gas exit velocity for both methods in Figure 2. From the graph, it can be seen that the plume rise predicted by Briggs' method exceeds that predicted by Holland's method under identical conditions, and that both methods exhibit similar sensitivities to changes in the gas exit velocity.

The computed plume rise is plotted against the gas exit temperature in Figure 3. From the graph, it can be seen that Briggs' method is more sensitive to the gas exit temperature than is Holland's method. However, it can also be seen that results for Briggs' method approach those for Holland's method at low gas exit temperatures. This implies that Briggs' method is equally applicable to cool sources contrary to the opinion of the ADPCE.

The ratio of the normalized concentrations computed using Briggs' method ($\tilde{C}_B$) to those computed using Holland's method ($\tilde{C}_H$) versus downwind distance is plotted in Figure 4. The wind speed indicated in the graph was assumed to be constant throughout the mixing layer. From the graph, it can be seen that Holland's method leads to higher predicted concentrations than does Briggs' method. The difference in predicted

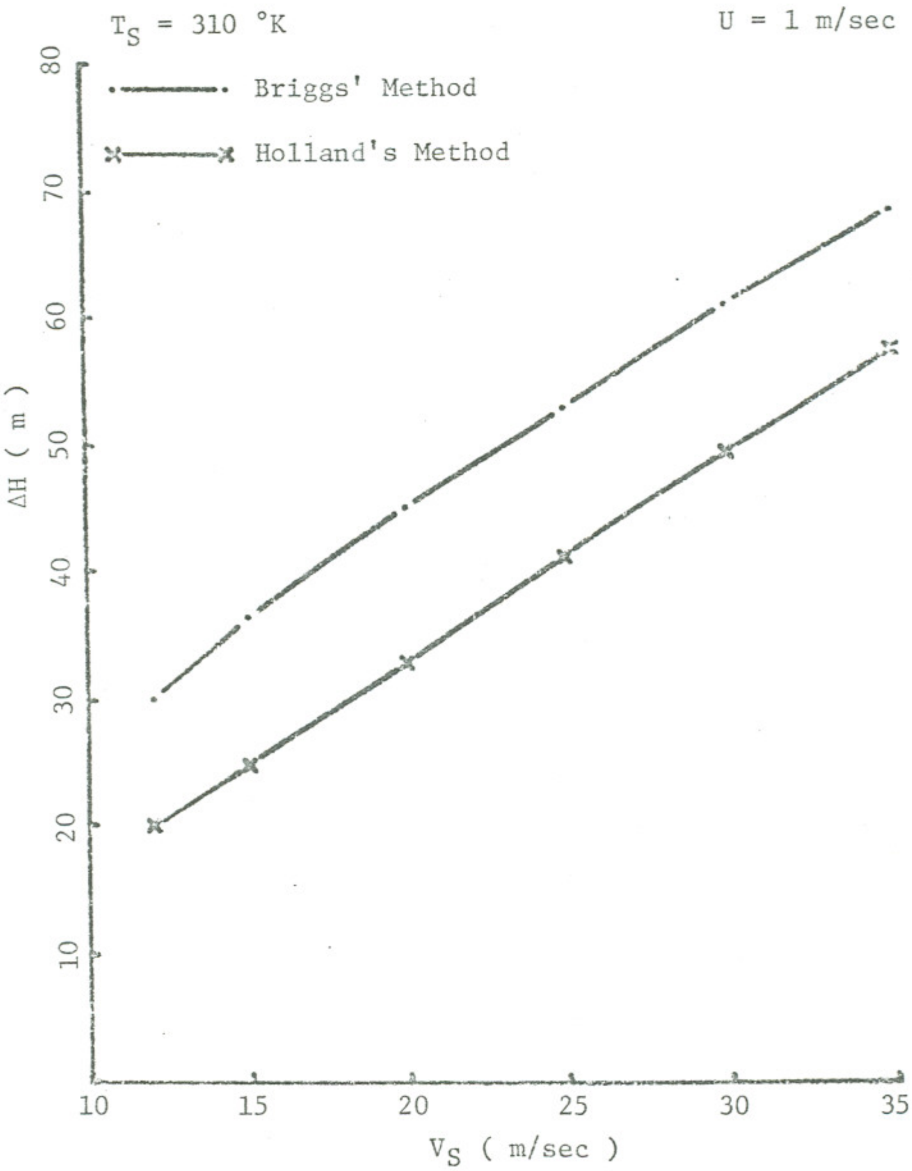


Figure 2. Plume rise versus gas exit velocity for Briggs' and Holland's plume rise computation methods.

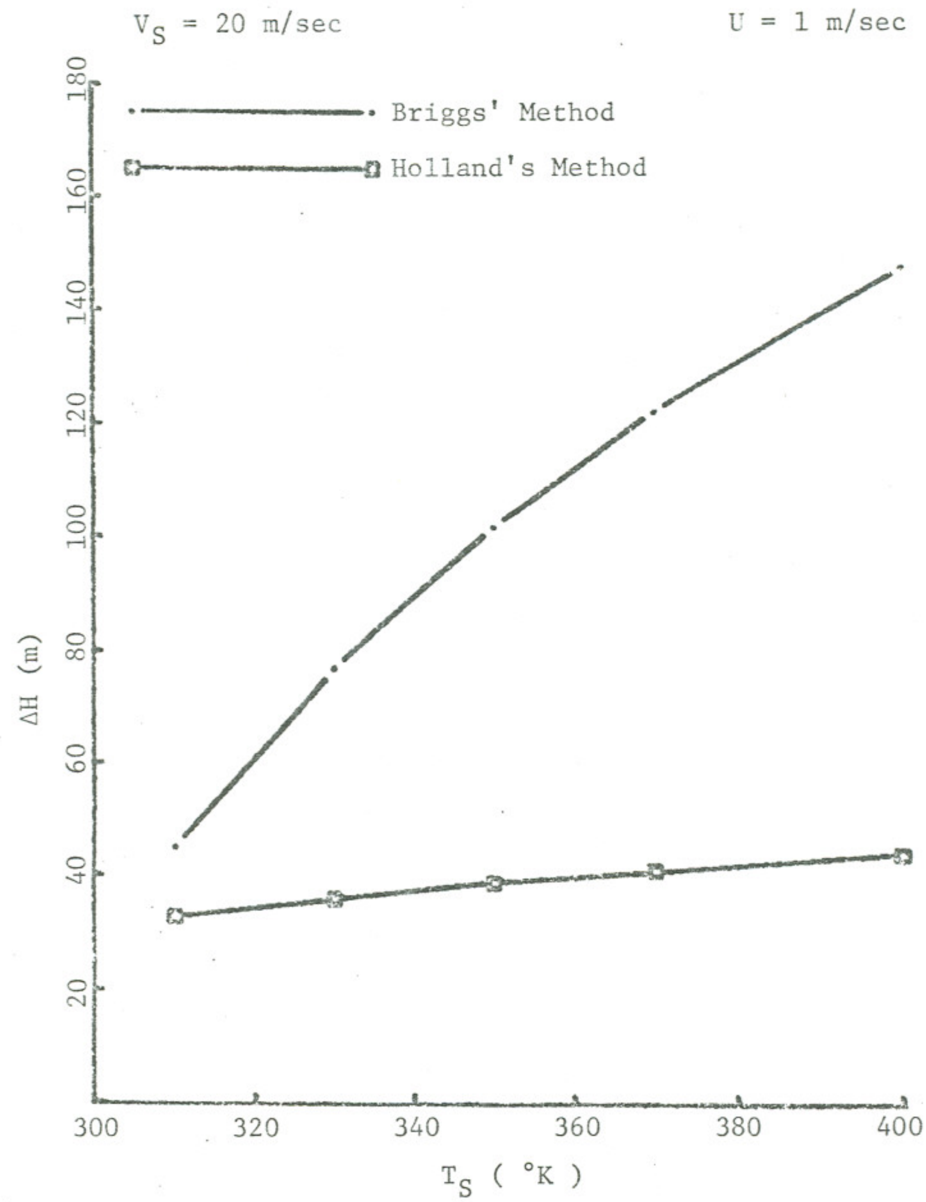


Figure 3. Plume rise versus gas exit temperature for Briggs' and Holland's plume rise computation methods.

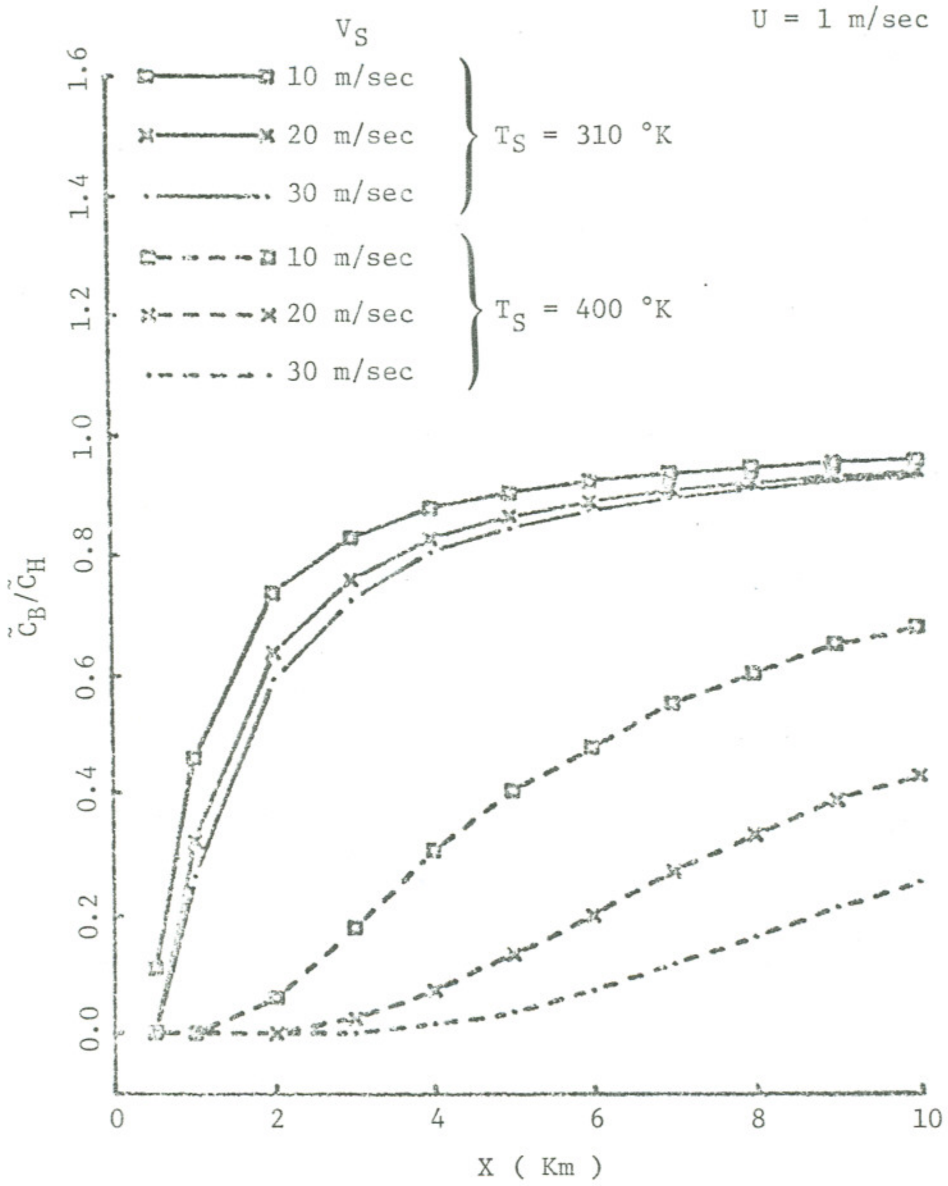


Figure 4. Ratio of normalized concentrations for Briggs' and Holland's methods versus distance from the source.

concentrations decreases with increasing downwind distance and decreasing gas exit velocity and temperature.

From the data presented above, it is apparent that the choice of a satisfactory algorithm for the plume height may be a critical factor in ICSE. The data presented here and the information presented by Briggs (1969) indicate that the indiscriminate use of Holland's method for a multiple stack system with a wide range in gas exit temperatures may lead to unreliable results. Briggs' method would be the more desirable algorithm for such a system.

The next parameters to be considered are $\sigma_y$ and $\sigma_z$ in Eq. 3. They are controlled by terrain features, atmospheric stability and wind speed. Turner (1970) graphically presented values for $\sigma_y$ and $\sigma_z$ for various atmospheric stability classes. These values apply to flat terrain (open rural areas). The presence of buildings and clustered trees, such as wood lots and forests, may significantly alter these values. The person conducting the ICSE should determine the necessity of conducting preliminary dispersion measurements for the area being considered.

The use of $\sigma_y$ and $\sigma_z$ values obtained from Turner's graphs is not conducive to rapid computation of concentrations at a multitude of downwind distances. A number of researchers (Tadmur and Gur, 1969; Eimutus and Konicek, 1972; McMullen, 1975) have developed empirical formulas for $\sigma_y$ and $\sigma_z$ based on numerical fits to Turner's graphical data. The computer program used during this study incorporated empirical formulas for $\sigma_y$ and $\sigma_z$ developed by Turner (see the program listing of subroutine DBTSIG in Appendix B).

The values of $\sigma_y$ and $\sigma_z$ are time-averaged quantities, and are observed to increase with increasing averaging time due to the effects of atmospheric turbulence. This means that mean concentrations decrease with increasing averaging time. The values of $\sigma_y$ and $\sigma_z$ presented by Turner (1969) apply to a 10 minute averaging time. Those used by the NTIS model PTMTP also apply to an averaging time of 10 minutes

Finally, consider the effect of the mean wind speed U on predicted concentrations. As indicated above, U controls the pollutant advection, the plume heights, and the dispersion coefficients. In Gaussian models, the mean wind speed is assumed to be constant (usually the mean surface wind speed) throughout the entire mixing layer. However, frictional effects at the Earth's surface diminishes the wind speed near the ground. The variation of friction with height causes the wind speed to increase with increasing altitude. Since the wind speed increases with height, the researcher must decide on the appropriate value of U to be used. Turner (1970) states that U should be the mean value averaged through the vertical region of the plume ($H - 2\sigma_z$ to $H + 2\sigma_z$). However, Turner indicates that generally only the surface wind speed is known making such an average impossible. The surface wind speed is only applicable to surface and low-level (low plume height) sources. Perkins (1974) suggests that the mean wind speed at the top of each stack be used. These values could be computed using the power law:

$$U_Z = U_1 \; (Z/Z_1)^n \tag{13}$$

where $U_Z$ is the wind speed at height Z, $U_1$ is the wind speed at height

$Z_1$, and n is a constant dependent upon the atmospheric stability. Seinfeld (1975) suggests that a power law is appropriate for the estimation of wind speeds throughout the mixing layer.

Consider the effect of a wind speed increase with height on plume heights. Briggs (1971) states that the value of U used in plume height computation routines should be the mean value averaged from the top of the stack to the top of the plume ($H + 2\sigma_z$). Briggs used such averaged values to check the validity of plume rise computations during one observational run (Briggs, 1977). Briggs (1977) states that the use of a hypothetical power law to determine the average wind speed through the plume rise layer is a legitimate procedure. However, Briggs also states that the use of such a power law to extrapolate wind speeds from a base height is risky for the following reasons:

1. The exponent n, determined experimentally, varies among researchers.
2. The exponent varies with atmospheric stability.
3. The exponent varies with surface roughness.
4. The exponent values are obtained through many observations and represent climatic averages. Wind speed profiles for individual observations often do not resemble the power law.
5. Climatological data (surface wind speeds) are generally taken at airports, which are generally more open and flat than surrounding sites. Thus, surface wind speeds and profiles observed at airports are generally different from those observed at surrounding sites.

These limitations in the power law make its routine use impractical for the industrial modeler. However, assumed values for the exponents can be used to indicate the qualitative effect of a variation in wind speed with height on predicted concentrations. Such an effect will be discussed for specific sources in Chapter IV.

# Chapter III

## APPLICATION OF A GAUSSIAN MODEL TO THE PINE BLUFF PROBLEM

Experimental Procedure:

Five sources of particulates were considered during the ICSE conducted for the Pine Bluff, Arkansas mill. It was initially believed that the recovery and bark boiler units would comprise the major sources of particulates outside of the plantsite. To evaluate the importance and the effectiveness of various control techniques for the abatement of pollutant emissions from these units, the lime slaker, kiln, and smelter stacks were also considered. The relative locations of these stacks are shown in Figure 5. The stack parameters and associated numbers, circled in Figure 5, are listed in Table I. The stack positions given in Table I are relative to the location of the recovery stack with $R_s$ oriented in the east-west direction and $S_s$ oriented in the north-south direction.

Six control strategies were considered during the study. These strategies can be grouped into three categories. In the first category, it was assumed that a wet scrubber would be used on the recovery stack. Two emission rates (scrubber efficiencies) for the recovery stack were evaluated. In the second control category, it was assumed that a dry precipitator would be used on the recovery stack, and two emission rates for the recovery stack were considered. In the third category, it was assumed that the effluent from the recovery and bark

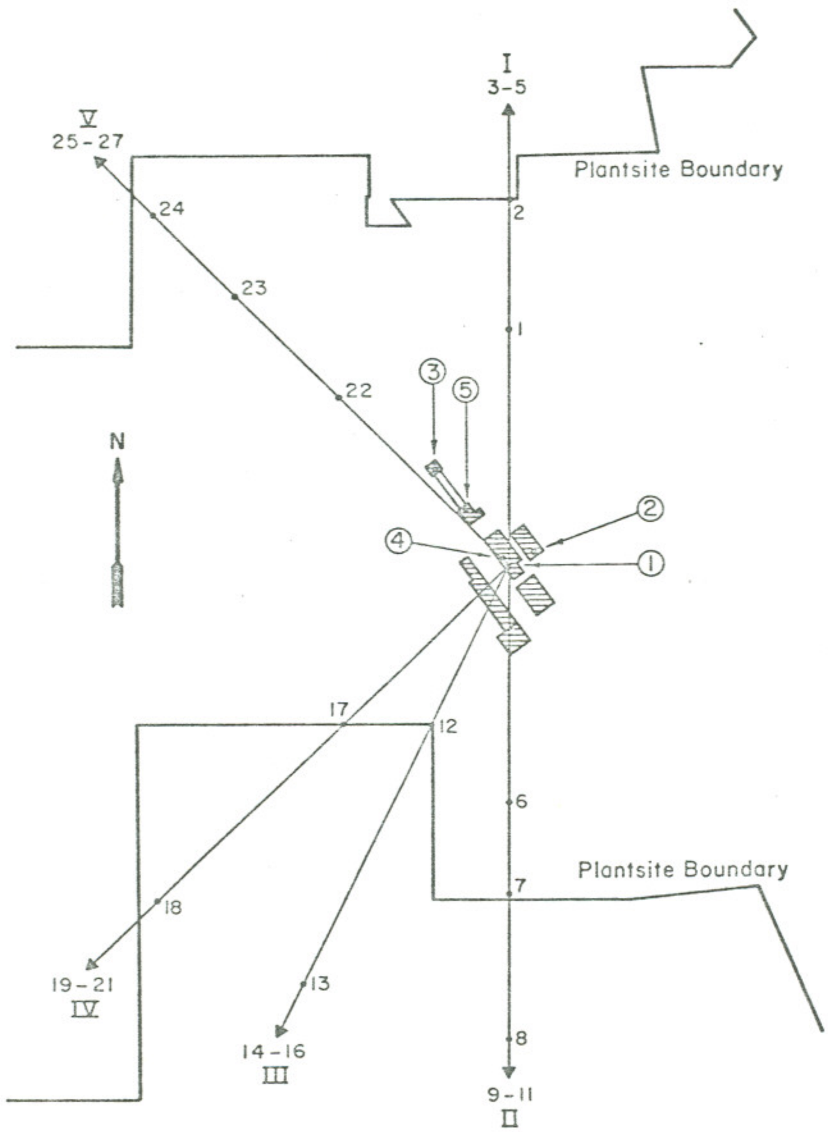


Figure 5. Source and receptor orientation.

TABLE I

STACK PARAMETERS

| Stack | Stack # | Height (M) | Inside Diameter (M) | $R_s$ (Km) | $S_s$ (Km) |
|---|---|---|---|---|---|
| Recovery | 1 | 45.7 | 2.1 | 0.000 | 0.000 |
| Bark Boiler | 2 | 21.0 | 1.4 | 0.060 | 0.030 |
| Kiln | 3 | 14.9 | 1.4 | -0.160 | 0.200 |
| Smelter | 4 | 29.0 | 0.9 | -0.010 | 0.049 |
| Slaker | 5 | 18.0 | 0.4 | -0.095 | 0.105 |

boiler units would be emitted from a common stack in the recovery stack location. The dimensions of this stack were assumed to be identical to those listed for the recovery stack in Table I. It was also assumed that a wet scrubber device would be used on the recovery unit prior to the combination of the effluent from the two units. Two scrubber efficiencies for the recovery unit were considered. Emission parameters for the various control techniques are listed in Table II. Each control strategy is designated by a system letter (A-F).

The NTIS-UNAMAP program PTMTP was used during this study. PTMTP incorporates basic Gaussian modeling techniques and utilizes Briggs' plume rise predictions for all sources. It allows the user to specify stack locations, stack dimensions, emission parameters, receptor sites, and meteorological conditions. It limits the user to a maximum of 26 point sources and 31 receptor sites. Any number of meteorological data sets may be considered. PTMTP incorporates the following assumptions:

1. The atmospheric stability class used is the same throughout the entire modeled area.
2. The stability characteristics are constant over the time period covered. PTMTP assumes an averaging time of 10 minutes.
3. The average wind velocity is constant in time and space.
4. Particle settling velocities are negligible.

Although the particulate size range for the Pine Bluff sources was not known prior to the modeling, it was assumed that settling effects would not be significant within three kilometers of the sources, which

TABLE II

EMISSION PARAMETERS

| Control Strategy | Stack | Emission Rate (G/SEC) | Gas Temperature (°K) | Exit Velocity (M/SEC) |
|---|---|---|---|---|
| A | Recovery | 22.8 | 345.2 | 10.8 |
| | Bark Boiler | 10.7 | 477.4 | 17.6 |
| B | Recovery | 11.4 | 345.2 | 10.8 |
| | Bark Boiler | 10.7 | 477.4 | 17.6 |
| C | Recovery | 22.8 | 449.7 | 10.8 |
| | Bark Boiler | 10.7 | 477.4 | 17.6 |
| D | Recovery | 11.4 | 449.7 | 10.8 |
| | Bark Boiler | 10.7 | 477.4 | 17.6 |
| E | Recovery/Bark Boiler | 33.6 | 376.1 | 21.9 |
| F | Recovery/Bark Boiler | 22.2 | 376.1 | 21.9 |
| All | Kiln | 1.5 | 343.6 | 5.8 |
| | Smelter | 1.9 | 346.9 | 7.3 |
| | Slaker | 1.3 | 308.0 | 1.0 |

was the distance covered by the study. Although PTMTP predicts concentrations for a 10 minute averaging time, it was assumed that the computed concentrations would be adequate for comparison to the ADPCE standard. Turner (1969) states that concentrations can be adjusted for averaging time by use of the equation:

$$\langle c \rangle_s = \langle c \rangle_k (t_k/t_s)^p$$

where $\langle c \rangle_s$ is the concentration for an averaging time $t_s$, $\langle c \rangle_k$ is the concentration for an averaging time $t_k$, and p is approximately 0.20. The concentration for an averaging time of 30 minutes is 20% smaller than that for averaging time of 10 minutes. This difference is well within the suggested accuracy of the Gaussian model and essentially may be ignored.

Since PTMTP limits the user to 31 receptor sites, it was decided to divide the receptors into groups of five and six along five directions radiating from the recovery stack location. These directions are labeled by Roman numerals (I-V) in Figure 5. Directions I, II, and II were chosen because the plantsite boundary lies relatively close to the recovery and bark boiler stacks. Directions IV and V were chosen to allow comparison of concentrations that can be expected for winds perpendicular to the line of stacks and along the line of stacks. Chosen receptor sites are number 1 through 27 in Figure 5. One receptor site along each direction was chosen to lie near the plantsite boundary. The other receptors were spaced more or less uniformly along the receptor strings up to 3 Km from the recovery stack. Some on-plantsite receptors were chosen to obtain concentrations relatively near the stacks. The orientation of the receptor strings and the locations of the receptors are listed in Table III.

The meteorological data used in the modeling were taken from Star Data compiled by the National Oceanic and Atmospheric Administration (NOAA) for the Little Rock, Arkansas area for the 1969-1973 period. Table IV summarizes the Star Data and lists the meteorological values selected for the study. Wind directions were selected such that the pollutants from the recovery stack would flow on average along the receptor strings.

Results:

To demonstrate the relative impact of the various sources, the computed partial and total concentrations are plotted against downwind distance along direction I for control strategy A in Figures 6, 7, and 8. Additional graphical data are presented in Appendix C. The computed results and these figures indicate:

1. The kiln stack is a relatively weak source of particulates at all locations under the selected meteorological conditions, and can essentially be ignored in further modeling studies.
2. The slaker stack is the major source of ground level particulates under low wind speed conditions. Its maximum offplantsite contribution occurs under neutral and stable conditions, leading to substantial predicted standard violations.
3. The recovery and bark boiler stacks are the major sources of

TABLE III

RECEPTOR LOCATIONS

| Direction From The Recovery Stack (Deg) | Receptor String # | Receptor # | Distance From The Recovery Stack (Km) |
|---|---|---|---|
| 0 | I | 1 | 0.50 |
| | | 2 | 1.00 |
| | | 3 | 1.50 |
| | | 4 | 2.00 |
| | | 5 | 3.00 |
| 180 | II | 6 | 0.50 |
| | | 7 | 0.70 |
| | | 8 | 1.00 |
| | | 9 | 1.50 |
| | | 10 | 2.00 |
| | | 11 | 3.00 |
| 205 | III | 12 | 0.381 |
| | | 13 | 1.00 |
| | | 14 | 1.50 |
| | | 15 | 2.00 |
| | | 16 | 3.00 |
| 225 | IV | 17 | 0.50 |
| | | 18 | 1.00 |
| | | 19 | 1.50 |
| | | 20 | 2.00 |
| | | 21 | 3.00 |
| 315 | V | 22 | 0.50 |
| | | 23 | 0.80 |
| | | 24 | 1.10 |
| | | 25 | 1.50 |
| | | 26 | 2.00 |
| | | 27 | 3.00 |

TABLE IV

STAR DATA AND METEOROLOGICAL DATA USED

| Stability Class | Wind Speed (M/SEC) | Percentage Of Observations | Wind Speed Used (M/SEC) |
|---|---|---|---|
| A | ≤ 0.5 | 0.075 | 0.3 |
| | 0.5 - 1.5 | 0.068 | 1.0 |
| | 2.1 - 3.1 | 0.64 | 3.0 |
| B | ≤ 0.5 | 0.12 | 0.3 |
| | 0.5 - 1.5 | 0.71 | 1.0 |
| | 2.1 - 3.1 | 3.7 | 3.0 |
| | 3.6 - 5.1 | 2.4 | 5.0 |
| C | ≤ 0.5 | 0.26 | 0.3 |
| | 0.5 - 1.5 | 0.28 | 1.0 |
| | 2.1 - 3.1 | 3.0 | 3.0 |
| | 3.6 - 5.1 | 7.9 | 5.0 |
| | 5.7 - 8.2 | 0.9 | - |
| | 8.7 - 10.8 | 0.01 | 11.0 |
| D | ≤ 0.5 | 0.03 | 0.3 |
| | 0.5 - 1.5 | 0.25 | - |
| | 2.1 - 3.1 | 5.0 | 3.0 |
| | 3.6 - 5.1 | 8.6 | - |
| | 5.7 - 8.2 | 7.8 | 6.0 |
| | 8.7 - 10.8 | 0.5 | 11.0 |
| | > 10.8 | 0.055 | 15.0 |
| E | ≤ 0.5 | 0.42 | 0.3 |
| | 0.5 - 1.5 | 0.62 | - |
| | 2.1 - 3.1 | 4.1 | 3.0 |
| | 3.6 - 5.1 | 9.4 | - |
| | 5.7 - 8.2 | 5.0 | 6.0 |
| | 8.7 - 10.8 | 0.45 | 11.0 |
| | > 10.8 | 0.075 | 15.0 |

TABLE IV

STAR DATA AND METEOROLOGICAL DATA USED

(cont.)

| Stability Class | Wind Speed (M/SEC) | Percentage Of Observations | Wind Speed Used (M/SEC) |
|---|---|---|---|
| F | ≤ 0.5 | 5.3 | 0.3 |
| | 0.5 - 1.5 | 4.6 | 1.0 |
| | 2.1 - 3.1 | 21.0 | 3.0 |
| | 3.6 - 5.1 | 6.8 | 5.0 |

MIXING HEIGHTS USED

| Stability Class | Mixing Height (M) |
|---|---|
| A | 2000 |
| B | 2000 |
| C | 2000 |
| D | 1000 |
| E | 500 |
| F | 300 |

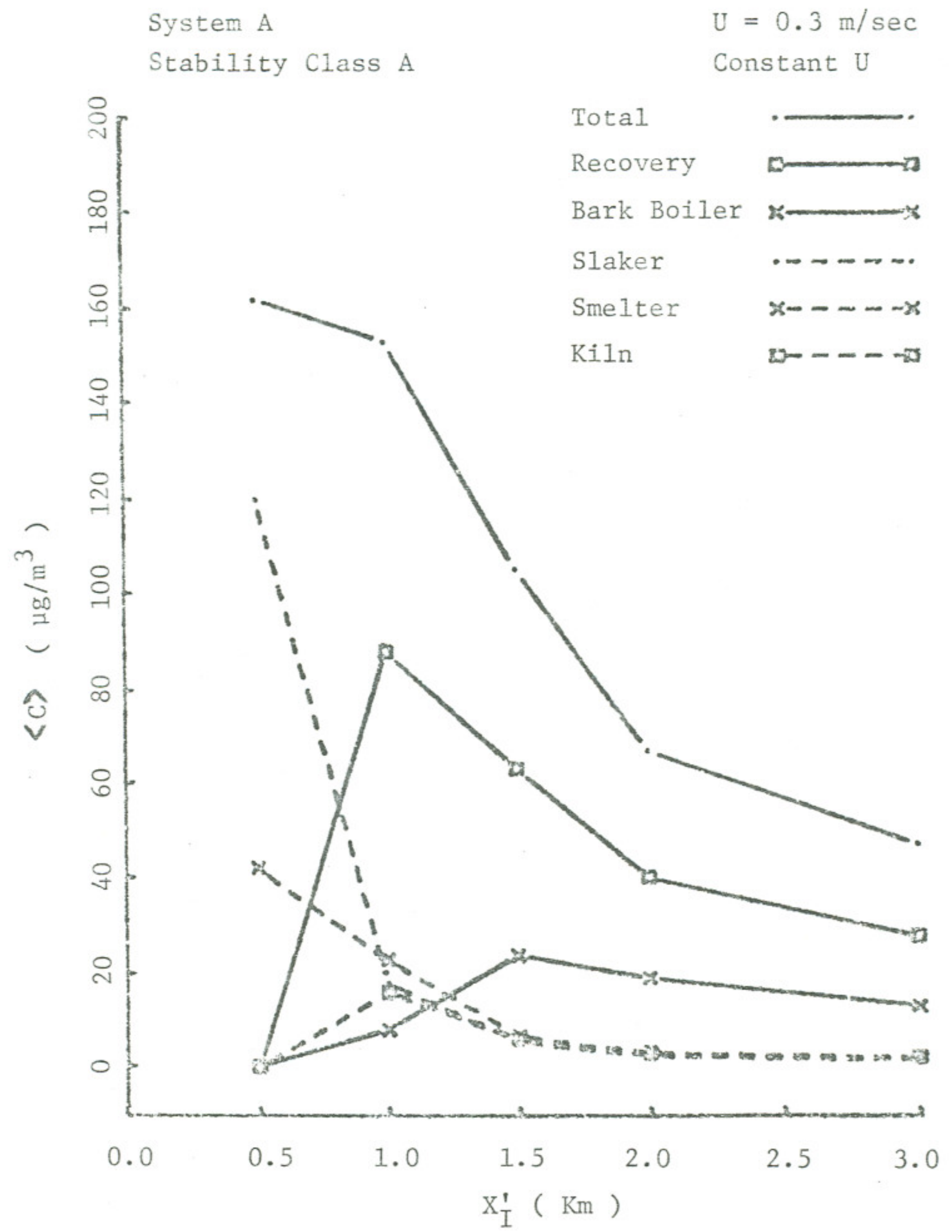


Figure 6. Ground level concentration versus distance along receptor string I.

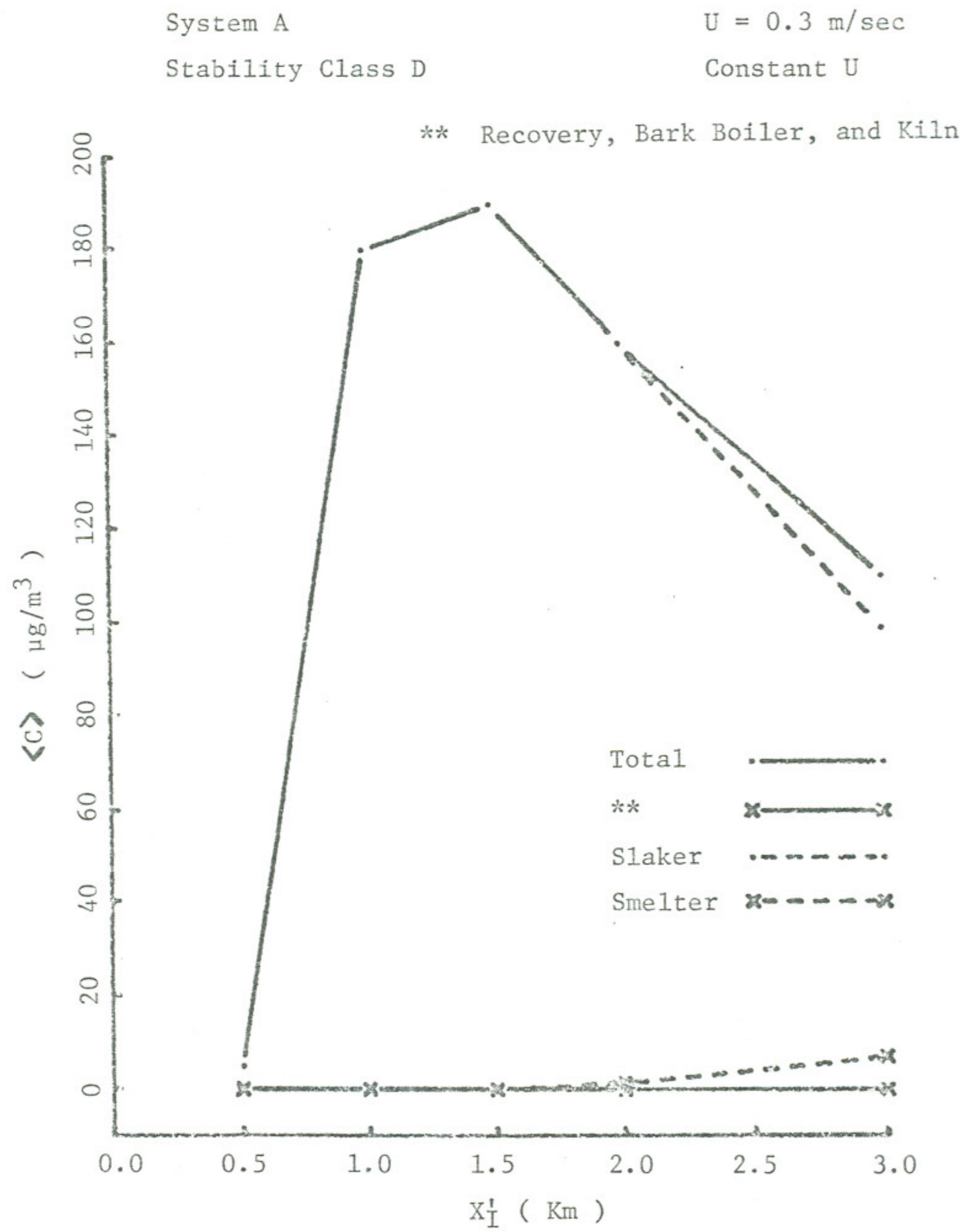


Figure 7. Ground level concentration versus distance along receptor string I.

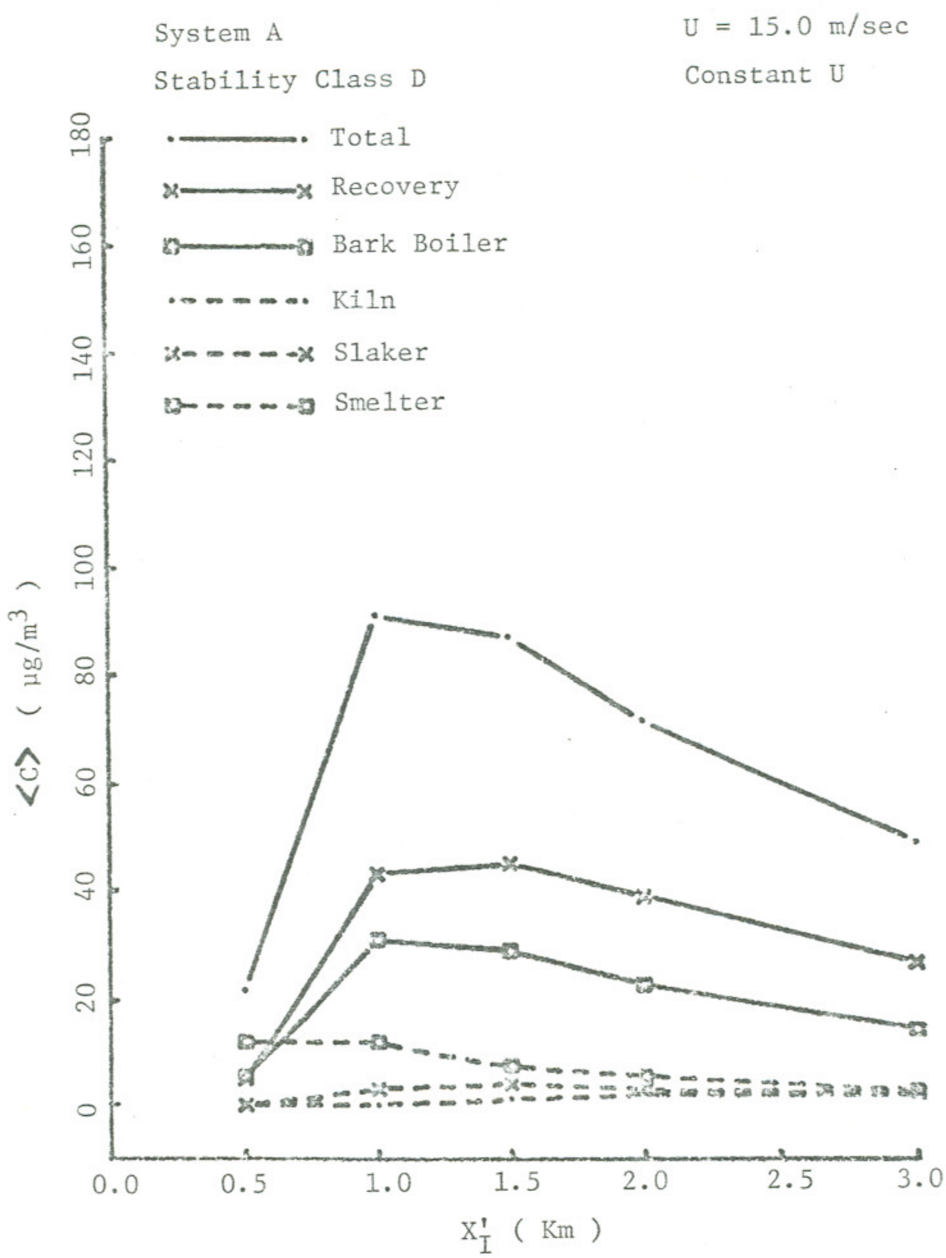


Figure 8. Ground level concentration versus distance along receptor string I.

ground level particulates for unstable and high wind speed conditions. The distance to the maximum concentration point exceeds 3 Km under stable conditions. However, as the distance to the maximum point increases, the maximum concentration decreases.

4. Control strategies C and E lead to a substantially lower contribution from the recovery stack at the plantsite boundary, thus avoiding the violation of the state standard as indicated for control strategy A in Figure 6.

The computed ground level concentrations are plotted against downwind distance for all of the control strategies in Figures 9, 10, and 11. Additional graphs are presented in Appendix C. These figures indicate:

1. Under unstable conditons, the partial concentrations from the recovery and bark boiler stacks at large downwind distances ( $x > 2$ Km) are sensitive only to the emission rates of the particulates and not to the control strategy type.
2. Under low wind speed and stable conditions, the choice of the most desirable control strategy is unimportant because the total concentration is controlled by the slaker emission. The highest off-plantsite concentrations are predicted under these conditions.
3. Control strategies E and F lead to the lowest off-plantsite concentrations under most meteorological conditions, whereas control strategies A and B lead to the highest concentrations.

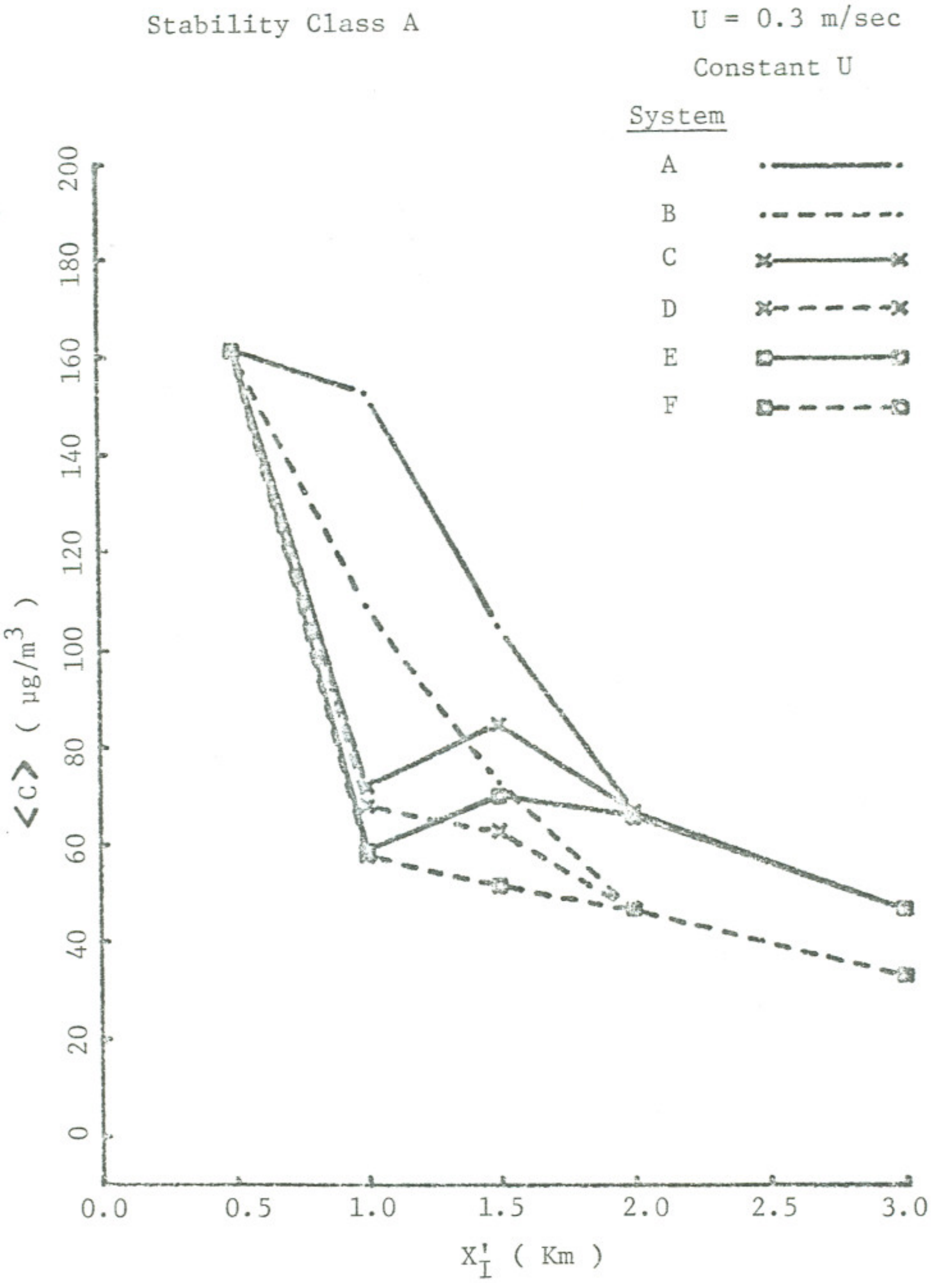


Figure 9. Ground level concentration versus distance along receptor string I for all control strategies.

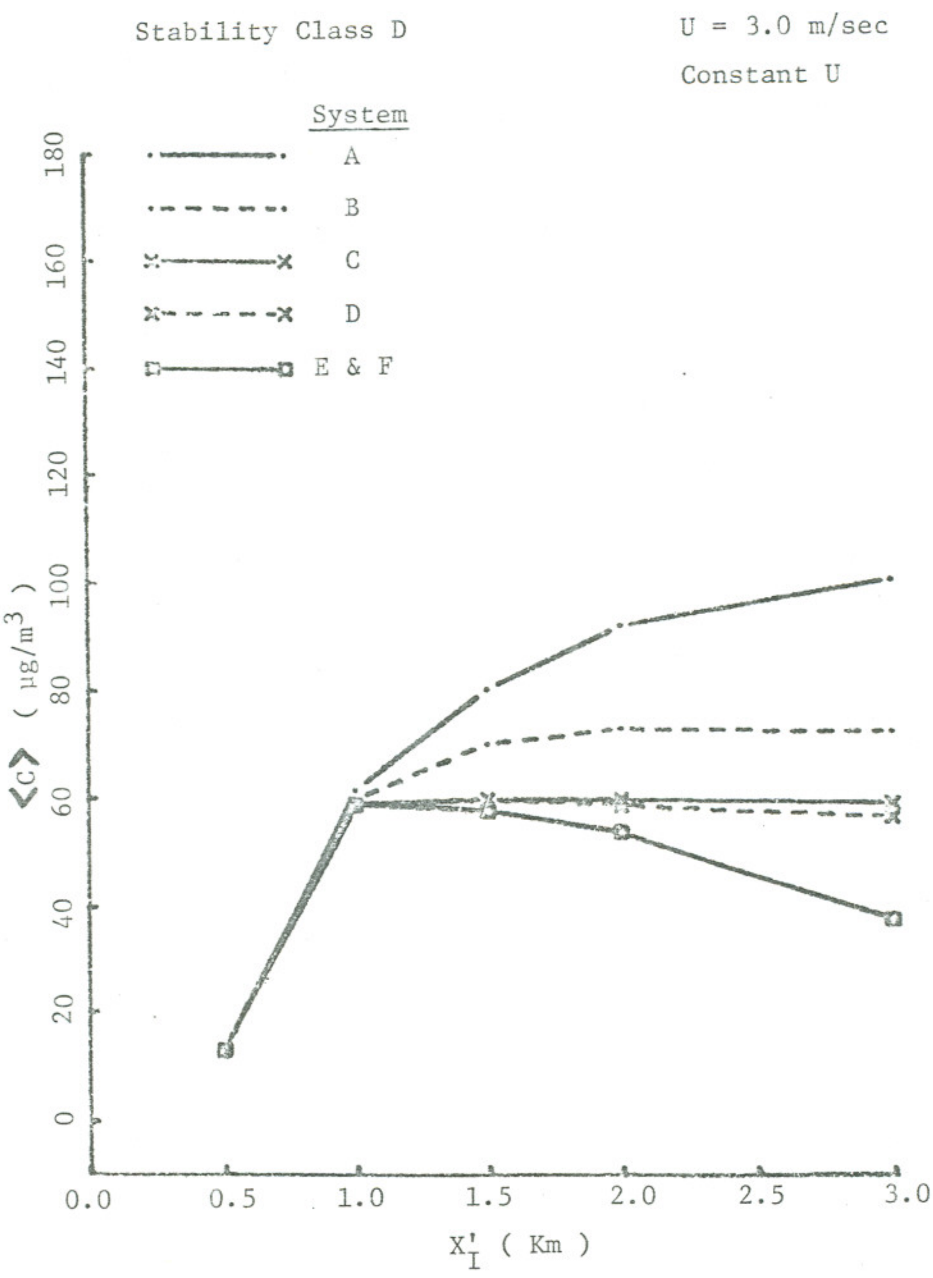


Figure 10. Ground level concentration versus distance along receptor string I for all control strategies.

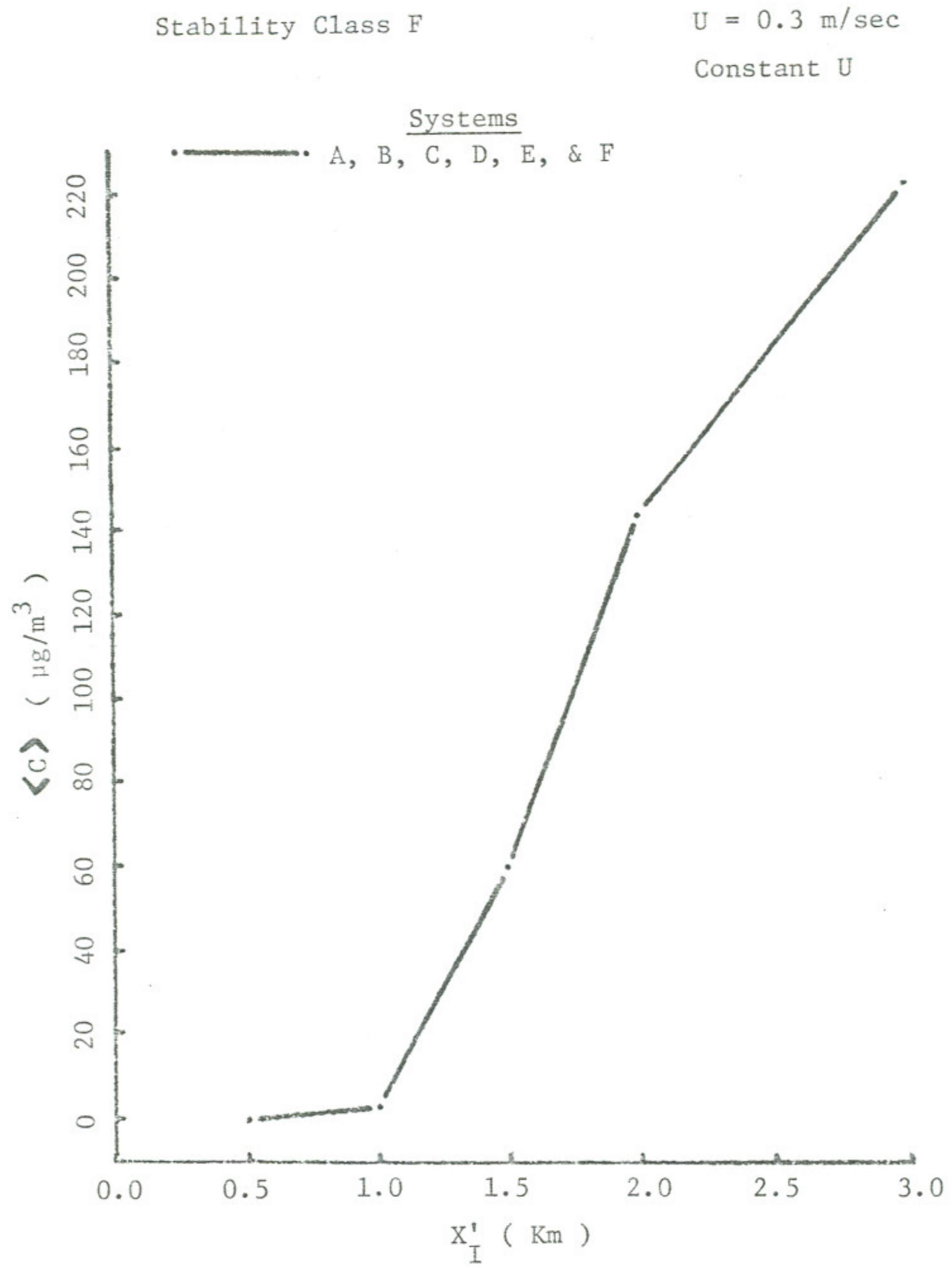


Figure 11. Ground level concentration versus distance along receptor string I for all control strategies.

Table V gives the summary of all predicted standard violations for the various control strategies and meteorological conditions. These data indicate that the recovery and bark boiler stacks contribute significantly to standard violations only for control strategy A. The slaker stack leads to violations for all control strategies.

After the modeling project was completed, it was discovered that the particles from the slaker stack are relatively large in size (some exceeding 20 μm in diameter) resulting in non-negligible settling velocities. The modeling results for the slaker stack were probably underestimated near the stack and overestimated at large downwind distances. It is possible (but not confirmed) that the slaker emission may not lead to violations of the state standard. If this source is responsible for standard violations, it is relatively easy to control by use of wet scrubbers or other techniques.

Assuming that the slaker emission can be controlled or ignored, all control strategies except A appear to be satisfactory for further consideration. All subsequent considerations should incorporate larger downwind distances up to or in excess of 10 Km to satisfactorly locate the maximum concentration points for the recovery and bark boiler effluents under stable conditions.

If the contribution from the slaker can not be ignored, future modeling efforts should account for the non-negligible settling velocity of the slaker particulates. This could be accomplished by using either numerical solutions to the general diffusion equation or a more general type of the Gaussian model such as that proposed

TABLE V

VIOLATIONS

Control System A:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.0 | A | 7 | 120 | 35 | 5 | 15 | 7 | 182 |
| | 3.0 | B | 7 | 100 | 34 | 6 | 18 | 9 | 167 |
| | 5.0 | B | 7 | 94 | 39 | 4 | 11 | 6 | 154 |
| | 0.3 | C | 7 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | C | 12 | 0 | 0 | 0 | 0 | 300 | 300 |
| | 5.0 | C | 8 | 92 | 39 | 4 | 15 | 7 | 157 |
| | 0.3 | D | 7 | 0 | 0 | 0 | 0 | 160 | 160 |
| | 0.3 | D | 8 | 0 | 0 | 0 | 0 | 200 | 200 |
| | 0.3 | D | 9 | 0 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | E | 9 | 0 | 0 | 3 | 14 | 180 | 197 |
| | 0.3 | E | 10 | 0 | 0 | 10 | 31 | 180 | 221 |
| | 0.3 | E | 11 | 6 | 3 | 25 | 51 | 140 | 225 |
| | 0.3 | F | 10 | 0 | 0 | 1 | 5 | 160 | 166 |
| | 0.3 | F | 11 | 0 | 0 | 7 | 20 | 200 | 227 |
| 25 | 3.0 | A | 12 | 110 | 45 | 2 | 22 | 7 | 186 |
| | 0.3 | B | 17 | 0 | 0 | 0 | 1 | 240 | 241 |
| | 0.3 | C | 17 | 0 | 0 | 0 | 0 | 450 | 450 |
| | 1.0 | C | 17 | 0 | 0 | 16 | 2 | 140 | 158 |
| | 5.0 | C | 13 | 92 | 42 | 2 | 15 | 6 | 157 |
| | 0.3 | D | 17 | 0 | 0 | 0 | 0 | 560 | 560 |
| | 0.3 | E | 15 | 0 | 0 | 2 | 30 | 120 | 150 |
| | 0.3 | E | 16 | 6 | 3 | 12 | 50 | 120 | 191 |

TABLE V (cont.)

Control System A:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 45 | 3.0 | A | 17 | 120 | 45 | 1 | 13 | 5 | 184 |
| | 5.0 | B | 17 | 93 | 49 | 0 | 18 | 4 | 164 |
| | 5.0 | C | 18 | 92 | 44 | 1 | 14 | 5 | 156 |
| | 0.3 | E | 21 | 6 | 3 | 8 | 49 | 110 | 176 |
| 135 | 0.3 | A | 24 | 95 | 19 | 22 | 16 | 16 | 169 |
| | 0.3 | C | 24 | 0 | 0 | 0 | 13 | 220 | 233 |
| | 0.3 | C | 25 | 0 | 0 | 2 | 28 | 120 | 150 |
| | 1.0 | C | 24 | 2 | 0 | 34 | 48 | 67 | 151 |
| | 3.0 | C | 24 | 89 | 27 | 26 | 23 | 22 | 187 |
| | 5.0 | C | 24 | 90 | 38 | 17 | 14 | 13 | 172 |
| | 0.3 | D | 24 | 0 | 0 | 0 | 0 | 530 | 530 |
| | 0.3 | D | 25 | 0 | 0 | 0 | 0 | 330 | 330 |
| | 0.3 | D | 26 | 0 | 0 | 0 | 2 | 220 | 222 |
| | 0.3 | E | 24 | 0 | 0 | 0 | 2 | 510 | 512 |
| | 0.3 | E | 25 | 0 | 0 | 5 | 10 | 420 | 435 |
| | 0.3 | E | 26 | 0 | 0 | 19 | 27 | 320 | 366 |
| | 0.3 | E | 27 | 6 | 3 | 41 | 49 | 200 | 299 |
| | 0.3 | F | 24 | 0 | 0 | 0 | 0 | 410 | 410 |
| | 0.3 | F | 25 | 0 | 0 | 0 | 0 | 500 | 500 |
| | 0.3 | F | 26 | 0 | 0 | 3 | 4 | 470 | 477 |
| | 0.3 | F | 27 | 0 | 0 | 18 | 18 | 350 | 386 |
| | 1.0 | F | 24 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 1.0 | F | 25 | 0 | 0 | 3 | 2 | 200 | 205 |
| | 1.0 | F | 26 | 0 | 0 | 13 | 9 | 170 | 192 |
| 135 | 1.0 | F | 27 | 2 | 3 | 28 | 21 | 120 | 174 |

TABLE V (cont.)

Control System A:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 180 | 0.3 | A | 2 | 88 | 8 | 16 | 23 | 18 | 153 |
| | 3.0 | B | 2 | 89 | 35 | 6 | 12 | 8 | 150 |
| | 0.3 | C | 2 | 0 | 0 | 0 | 8 | 150 | 158 |
| | 3.0 | C | 2 | 82 | 22 | 5 | 27 | 15 | 151 |
| | 3.0 | C | 3 | 88 | 32 | 7 | 14 | 9 | 150 |
| | 5.0 | C | 2 | 92 | 39 | 3 | 17 | 9 | 160 |
| | 0.3 | D | 2 | 0 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | D | 3 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 0.3 | D | 4 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | E | 2 | 0 | 0 | 0 | 11 | 160 | 171 |
| | 0.3 | E | 3 | 0 | 0 | 4 | 28 | 180 | 212 |
| | 0.3 | E | 4 | 6 | 3 | 20 | 50 | 150 | 229 |
| | 0.3 | F | 5 | 0 | 0 | 4 | 19 | 200 | 223 |
| Control System B: | | | | | | | | | |
| 0 | 0.3 | C | 7 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | C | 12 | 0 | 0 | 0 | 0 | 330 | 330 |
| | 0.3 | D | 7 | 0 | 0 | 0 | 0 | 160 | 160 |
| | 0.3 | D | 8 | 0 | 0 | 0 | 0 | 200 | 200 |
| | 0.3 | D | 9 | 0 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | E | 9 | 0 | 0 | 3 | 14 | 180 | 197 |
| | 0.3 | E | 10 | 0 | 0 | 10 | 31 | 180 | 221 |
| | 0.3 | E | 11 | 3 | 3 | 25 | 51 | 140 | 222 |
| | 0.3 | F | 10 | 0 | 0 | 1 | 5 | 160 | 166 |
| | 0.3 | F | 11 | 0 | 0 | 7 | 20 | 200 | 227 |
| 25 | 0.3 | B | 17 | 0 | 0 | 0 | 1 | 240 | 241 |
| | 0.3 | C | 17 | 0 | 0 | 0 | 0 | 450 | 450 |

TABLE V (cont.)

Control System B:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 25 | 1.0 | C | 17 | 0 | 0 | 16 | 2 | 140 | 158 |
| | 0.3 | D | 17 | 0 | 0 | 0 | 0 | 560 | 560 |
| | 0.3 | E | 15 | 0 | 0 | 2 | 30 | 120 | 152 |
| | 0.3 | E | 16 | 3 | 3 | 12 | 50 | 120 | 188 |
| 45 | 0.3 | E | 21 | 3 | 3 | 8 | 49 | 110 | 173 |
| 135 | 0.3 | C | 24 | 0 | 0 | 0 | 13 | 220 | 233 |
| | 0.3 | C | 25 | 0 | 0 | 2 | 28 | 120 | 150 |
| | 1.0 | C | 24 | 1 | 0 | 34 | 48 | 67 | 150 |
| | 0.3 | D | 24 | 0 | 0 | 0 | 0 | 530 | 530 |
| | 0.3 | D | 25 | 0 | 0 | 0 | 0 | 330 | 330 |
| | 0.3 | D | 26 | 0 | 0 | 0 | 2 | 220 | 222 |
| | 0.3 | E | 24 | 0 | 0 | 0 | 2 | 510 | 512 |
| | 0.3 | E | 25 | 0 | 0 | 5 | 10 | 420 | 435 |
| | 0.3 | E | 26 | 0 | 0 | 19 | 27 | 320 | 366 |
| | 0.3 | E | 27 | 3 | 3 | 41 | 49 | 200 | 296 |
| | 0.3 | F | 24 | 0 | 0 | 0 | 0 | 410 | 410 |
| | 0.3 | F | 25 | 0 | 0 | 0 | 0 | 500 | 500 |
| | 0.3 | F | 26 | 0 | 0 | 3 | 4 | 470 | 477 |
| | 0.3 | F | 27 | 0 | 0 | 18 | 18 | 350 | 386 |
| | 1.0 | F | 24 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 1.0 | F | 25 | 0 | 0 | 3 | 2 | 200 | 205 |
| | 1.0 | F | 26 | 0 | 0 | 13 | 9 | 170 | 192 |
| | 1.0 | F | 27 | 1 | 3 | 28 | 21 | 120 | 173 |
| 180 | 0.3 | C | 2 | 0 | 0 | 0 | 8 | 150 | 158 |
| | 0.3 | D | 2 | 0 | 0 | 0 | 0 | 180 | 180 |

TABLE V (cont.)

Control System B:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 180 | 0.3 | D | 3 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 0.3 | D | 4 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | E | 2 | 0 | 0 | 0 | 11 | 160 | 171 |
| | 0.3 | E | 3 | 0 | 0 | 4 | 28 | 180 | 212 |
| | 0.3 | E | 4 | 3 | 3 | 20 | 50 | 150 | 226 |
| | 0.3 | F | 5 | 0 | 0 | 4 | 19 | 200 | 223 |

Control System C and D:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery ($\mu g/m^3$) | Bark Boiler ($\mu g/m^3$) | Kiln ($\mu g/m^3$) | Smelter ($\mu g/m^3$) | Slaker ($\mu g/m^3$) | Total ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.3 | B | 12 | 0 | 0 | 0 | 0 | 240 | 240 |
| | 0.3 | C | 7 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | C | 12 | 0 | 0 | 0 | 0 | 300 | 300 |
| | 0.3 | D | 7 | 0 | 0 | 0 | 0 | 160 | 160 |
| | 0.3 | D | 8 | 0 | 0 | 0 | 0 | 200 | 200 |
| | 0.3 | D | 9 | 0 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | E | 9 | 0 | 0 | 3 | 14 | 180 | 197 |
| | 0.3 | E | 10 | 0 | 0 | 10 | 31 | 180 | 221 |
| | 0.3 | E | 11 | 0 | 3 | 25 | 51 | 140 | 219 |
| | 0.3 | F | 10 | 0 | 0 | 1 | 5 | 160 | 166 |
| | 0.3 | F | 11 | 0 | 0 | 7 | 20 | 200 | 227 |
| 25 | 0.3 | B | 17 | 0 | 0 | 0 | 1 | 240 | 241 |
| | 0.3 | C | 17 | 0 | 0 | 0 | 0 | 450 | 450 |
| | 1.0 | C | 17 | 0 | 0 | 16 | 2 | 140 | 158 |
| | 0.3 | D | 17 | 0 | 0 | 0 | 0 | 560 | 560 |
| | 0.3 | E | 15 | 0 | 0 | 2 | 30 | 120 | 152 |
| | 0.3 | E | 16 | 0 | 3 | 12 | 50 | 120 | 185 |
| 45 | 0.3 | E | 21 | 0 | 3 | 8 | 49 | 110 | 170 |

TABLE V (cont.)

Control Strategies C and D:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery (μg/m³) | Bark Boiler (μg/m³) | Kiln (μg/m³) | Smelter (μg/m³) | Slaker (μg/m³) | Total (μg/m³) |
|---|---|---|---|---|---|---|---|---|---|
| 135 | 0.3 | C | 24 | 0 | 0 | 0 | 13 | 220 | 233 |
| | 0.3 | C | 24 | 0 | 0 | 2 | 28 | 120 | 150 |
| | 0.3 | D | 24 | 0 | 0 | 0 | 0 | 530 | 530 |
| | 0.3 | D | 25 | 0 | 0 | 0 | 0 | 340 | 340 |
| | 0.3 | D | 26 | 0 | 0 | 0 | 2 | 220 | 222 |
| | 0.3 | E | 24 | 0 | 0 | 0 | 2 | 510 | 512 |
| | 0.3 | E | 25 | 0 | 0 | 5 | 10 | 420 | 435 |
| | 0.3 | E | 26 | 0 | 0 | 19 | 27 | 320 | 366 |
| | 0.3 | F | 24 | 0 | 0 | 0 | 0 | 410 | 410 |
| | 0.3 | F | 25 | 0 | 0 | 0 | 0 | 500 | 500 |
| | 0.3 | F | 26 | 0 | 0 | 3 | 4 | 470 | 477 |
| | 0.3 | F | 27 | 0 | 0 | 18 | 18 | 350 | 386 |
| | 1.0 | F | 24 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 1.0 | F | 25 | 0 | 0 | 3 | 2 | 200 | 205 |
| | 1.0 | F | 26 | 0 | 0 | 13 | 9 | 170 | 192 |
| | 1.0 | F | 27 | 0 | 3 | 28 | 21 | 120 | 169 |
| 180 | 0.3 | C | 2 | 0 | 0 | 0 | 8 | 150 | 158 |
| | 0.3 | D | 2 | 0 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | D | 3 | 0 | 0 | 0 | 0 | 190 | 190 |
| | 0.3 | D | 4 | 0 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | E | 3 | 0 | 0 | 0 | 11 | 160 | 171 |
| | 0.3 | E | 4 | 0 | 0 | 4 | 28 | 180 | 212 |
| | 0.3 | E | 5 | 0 | 3 | 20 | 50 | 150 | 223 |
| | 0.3 | F | 5 | 0 | 0 | 4 | 19 | 200 | 222 |

TABLE V (cont.)

Control Strategies E and F:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery/ Bark Boiler (μg/m$^3$) | Kiln (μg/m$^3$) | Smelter (μg/m$^3$) | Slaker (μg/m$^3$) | Total (μg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.3 | B | 12 | 0 | 0 | 0 | 240 | 240 |
| | 0.3 | C | 7 | 0 | 0 | 2 | 160 | 162 |
| | 0.3 | C | 12 | 0 | 0 | 0 | 300 | 300 |
| | 0.3 | D | 7 | 0 | 0 | 0 | 160 | 160 |
| | 0.3 | D | 8 | 0 | 0 | 0 | 200 | 200 |
| | 0.3 | D | 9 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | E | 9 | 0 | 3 | 14 | 180 | 197 |
| | 0.3 | E | 10 | 0 | 10 | 31 | 180 | 221 |
| | 0.3 | E | 11 | 0 | 25 | 51 | 140 | 216 |
| | 0.3 | F | 10 | 0 | 1 | 5 | 160 | 166 |
| | 0.3 | F | 11 | 0 | 7 | 20 | 200 | 227 |
| 25 | 0.3 | B | 17 | 0 | 0 | 1 | 240 | 241 |
| | 0.3 | C | 17 | 0 | 0 | 0 | 450 | 450 |
| | 1.0 | C | 17 | 0 | 16 | 2 | 140 | 158 |
| | 0.3 | D | 17 | 0 | 0 | 0 | 560 | 560 |
| | 0.3 | E | 15 | 0 | 2 | 30 | 120 | 152 |
| | 0.3 | E | 16 | 0 | 12 | 50 | 120 | 182 |
| 45 | 0.3 | E | 21 | 0 | 8 | 49 | 110 | 167 |
| 135 | 0.3 | C | 24 | 0 | 0 | 13 | 220 | 233 |
| | 0.3 | C | 25 | 0 | 2 | 28 | 120 | 150 |
| | 0.3 | D | 24 | 0 | 0 | 0 | 530 | 530 |
| | 0.3 | D | 25 | 0 | 0 | 0 | 340 | 340 |
| | 0.3 | D | 26 | 0 | 0 | 2 | 220 | 222 |
| | 0.3 | E | 24 | 0 | 0 | 2 | 510 | 512 |
| | 0.3 | E | 25 | 0 | 5 | 10 | 420 | 435 |

TABLE V (cont.)

Control Strategies E and F:

| W.D. (°) | W.S. (m/sec) | St. | R. # | Recovery/ Bark Boiler (μg/m³) | Kiln (μg/m³) | Smelter (μg/m³) | Slaker (μg/m³) | Total (μg/m³) |
|---|---|---|---|---|---|---|---|---|
| 135 | 0.3 | E | 26 | 0 | 19 | 27 | 320 | 366 |
| | 0.3 | F | 24 | 0 | 0 | 0 | 410 | 410 |
| | 0.3 | F | 25 | 0 | 0 | 0 | 500 | 500 |
| | 0.3 | F | 26 | 0 | 3 | 4 | 470 | 477 |
| | 0.3 | F | 27 | 0 | 18 | 18 | 350 | 386 |
| | 0.3 | F | 24 | 0 | 0 | 0 | 190 | 190 |
| | 0.3 | F | 25 | 0 | 3 | 2 | 200 | 205 |
| | 0.3 | F | 26 | 0 | 13 | 9 | 170 | 192 |
| | 0.3 | F | 27 | 0 | 28 | 21 | 120 | 169 |
| 180 | 0.3 | C | 2 | 0 | 0 | 8 | 150 | 158 |
| | 0.3 | D | 2 | 0 | 0 | 0 | 180 | 180 |
| | 0.3 | D | 3 | 0 | 0 | 0 | 190 | 190 |
| | 0.3 | E | 3 | 0 | 0 | 11 | 160 | 171 |
| | 0.3 | E | 4 | 0 | 4 | 28 | 180 | 212 |
| | 0.3 | E | 5 | 0 | 20 | 50 | 150 | 220 |
| | 0.3 | F | 5 | 0 | 4 | 19 | 200 | 222 |

by Overcamp (1976) which incorporates particle deposition considerations. Actual particulate concentration measurements should be made in the vicinity of the slaker stack to determine the necessity of using these models.

# Chapter IV

## THE EFFECT OF THE CHANGE OF WIND SPEED WITH HEIGHT ON THE PINE BLUFF RESULTS

As previously indicated, the Pine Bluff, Arkansas ICSE study assumed a constant wind speed. However, as indicated in Chapter II, this is often not a valid assumption. This chapter presents a reevaluation of the ICSE assuming the wind speed obeys the power law profile described in Chapter II. The wind speed profile exponents of Perkins (1974):

$n = 0.25$ stable conditions

$= 0.50$ unstable conditions

were used.

PTMTP was modified to evaluate the effects of the wind speed profile on computed considerations. The main modifications were made in the subroutines used to compute the plume heights and the relative concentrations. A copy of this program is presented in Appendix B.

As a preliminary investigation, the modified program was used for single sources. Figure 12 shows the results for the recovery stack assuming control strategy C. The wind speeds indicated in this figure and those to follow are the assumed values at $Z = 10$ m. From the graph, it can be seen that the use of the wind speed profile results in a shift of the point of maximum concentration towards the stack relative to the results for a constant wind speed. This shift leads to an increase in the ground level concentration near the stack

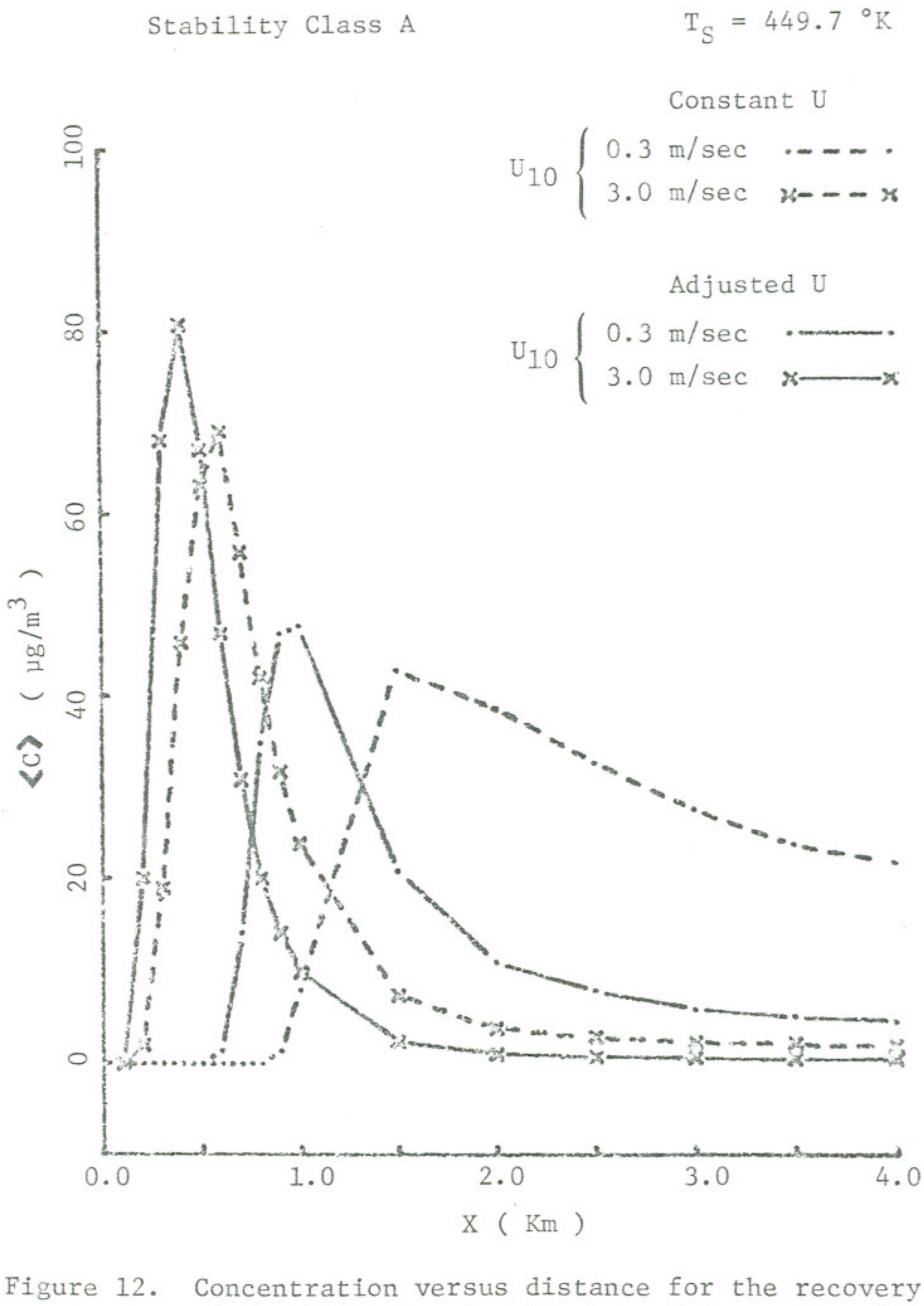


Figure 12. Concentration versus distance for the recovery stack effluent under the two wind speed profile assumptions.

and a decrease at large downwind distances. It can also be seen that the major differences between the concentrations for the two assumptions occur at low wind speeds.

Figures 13 and 14 show the results for the slaker stack under the meteorological conditions considered in the previous figure. It can be noted that the differences in concnetration between the two assumptions are small due to a minimal plume rise for the slaker stack effluent compared to that of the recovery effluent.

Figure 15 shows the total concentrations computed for the ICSE under the two wind speed assumptions. Control strategies A and E were selected as being representative of the various emission parameter possibilities. This figure indicates that the assumption of a constant wind speed may lead to an overestimation of ground level concentrations, particularly at large downwind distances ( $x \gtrsim 2$ Km). The largest differences are indicated for those locations and conditions where the recovery and bark boiler stacks are the dominant sources.

Due to the difficulties involved in the use of the power law profile, the magnitudes of the differences in the results indicated above should not be considered as absolute values. Since the exponents used were averages over many conditions, these results serve only to indicate a possible artifact of the Gaussian model under a constant wind speed assumption. However, the results do indicate that the number of standard violations listed in Table V is a conservative estimate.

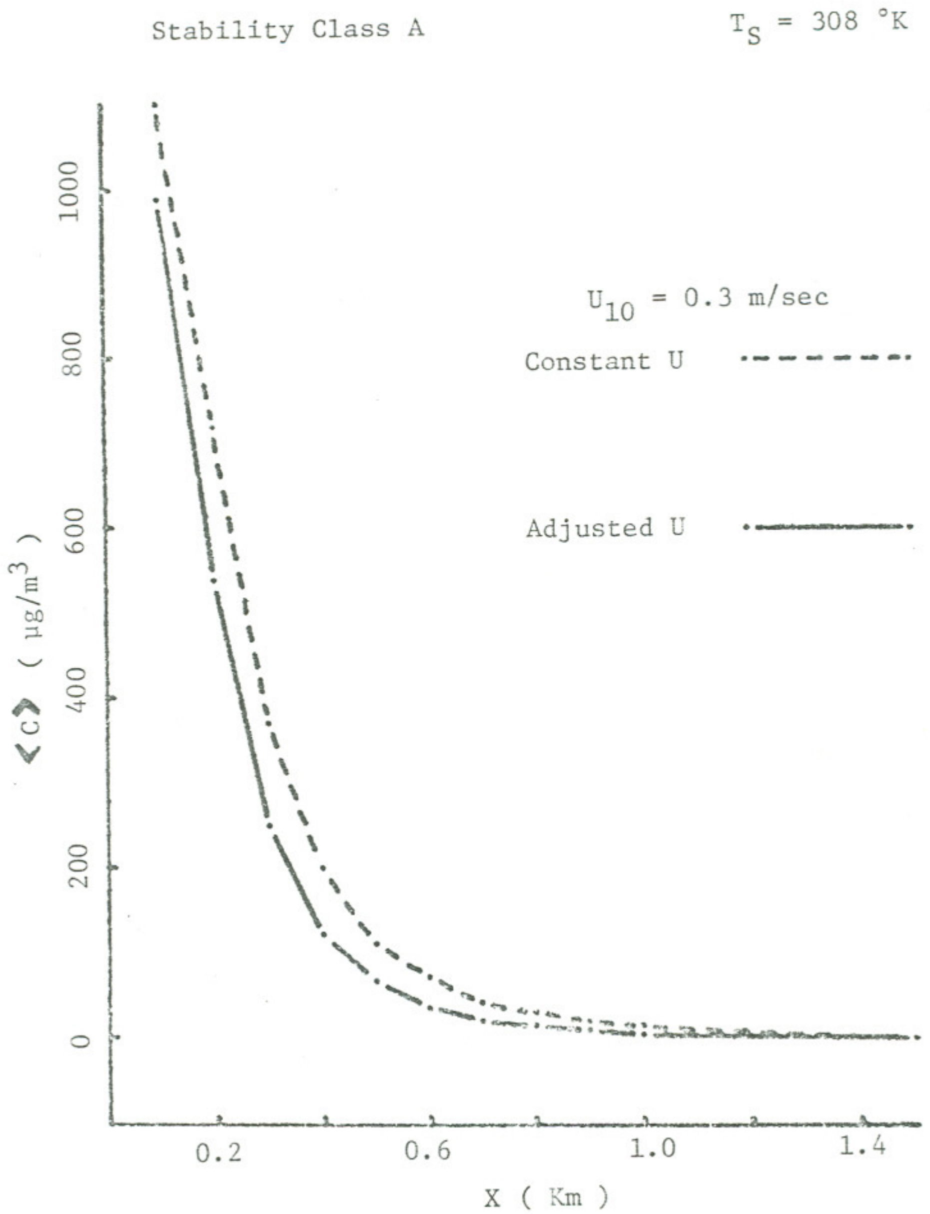


Figure 13. Concentration versus distance for the slaker stack effluent under the two wind speed profile assumptions.

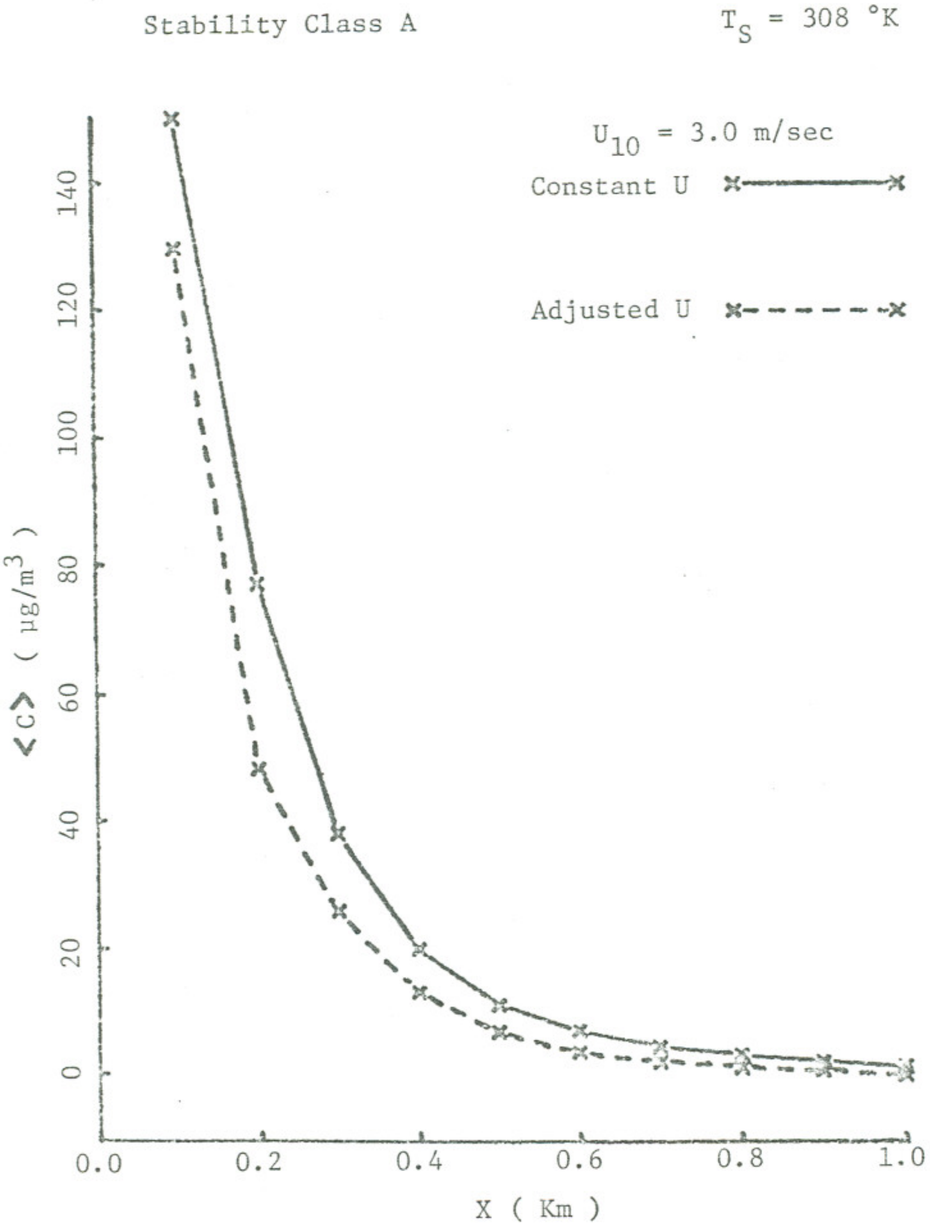


Figure 14. Concentration versus distance for the slaker stack effluent under the two wind speed profile assumptions.

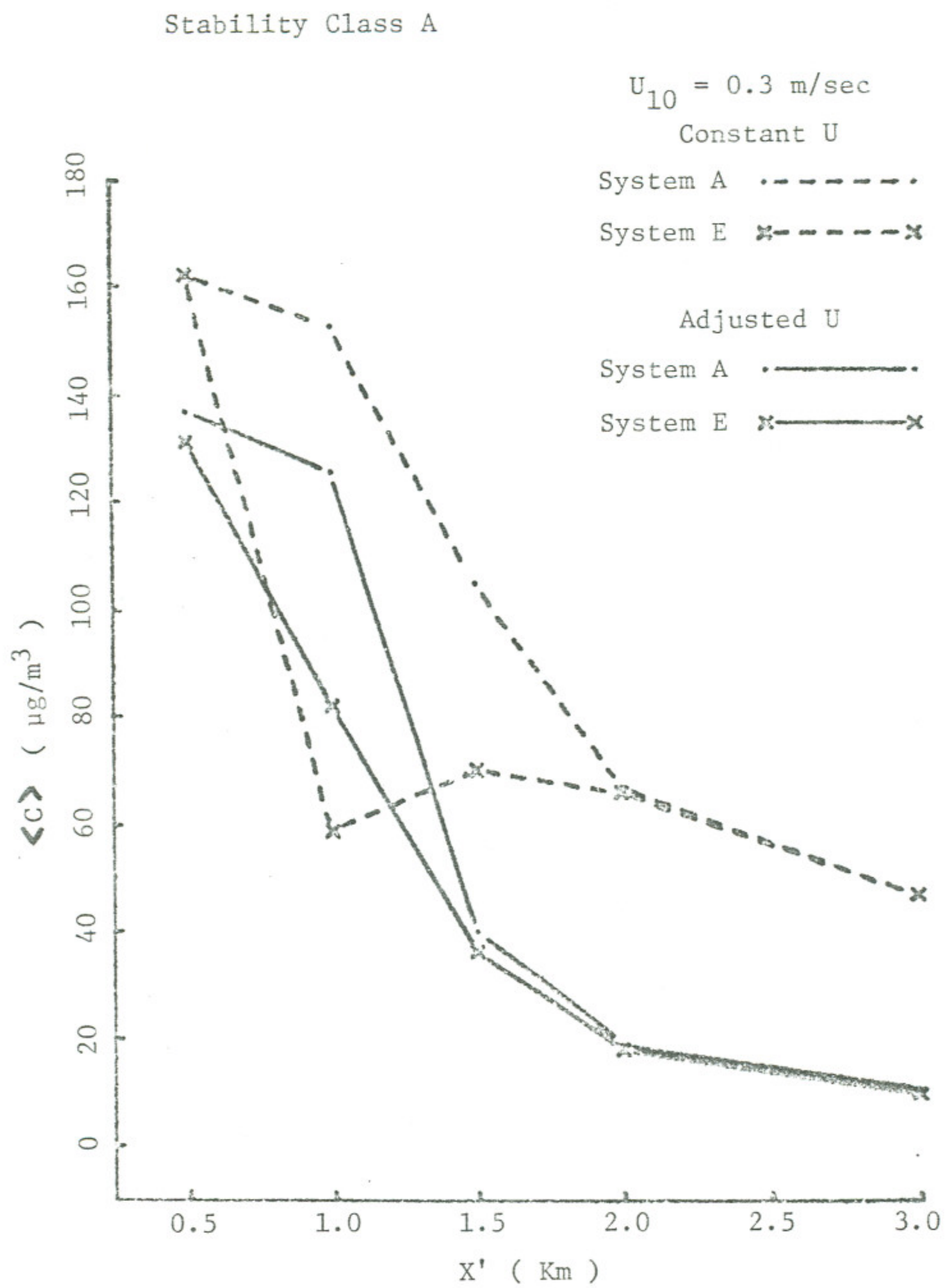


Figure 15. Concentration versus distance along receptor string I for the two wind speed profile assumptions.

# Chapter V

# CONCLUSION

## A. The Pine Bluff, Arkansas Control Strategy Evaluation:

The results of the study indicate that out of the possible control strategies evaluated and over the downwind distances covered, the only unstaisfactory control method would be the use of a wet scrubber on the recovery stack with an emission rate of 22.8 g/sec. The most desirable control technique, from an off-plantsite standpoint, is the combination of the recovery and bark boiler emissions through a single stack (systems E and F).

The results indicate that the slaker emissions may lead to substantial standard violations under neutral and stable atmospheric conditions. These predictions may be an artifact of the Gaussian model due its inability to simulate particle settling effects. In the statements made in the previous paragraph, it was assumed that the high concentrations from the slaker stack would not actually occur at off-plantsite locations or that the slaker emission can be easily controlled. Particulate concentration measurements should be made both on and off of the plantsite to establish the necessity of further consideration of the slaker emission level.

The results indicate that future modeling projects should consider downwind distances in excess of 10 Km. Such projects should also take into account the ambient background concentration of particulates, which was assumed to be negligible in this study.

## B. Wind Speed Profile Effects:

The results show that the choice of the wind speed profile can influence control strategy modeling results. The main effect of an increase in the wind speed with height is an increase in the computed concentration near a source and a decrease at larger downwind distances in comparison to results for a constant wind speed.

A researcher should take this effect into consideration. In practice it would be risky to assume that a particular wind speed profile is applicable for all occasions. A power law profile represents a climatological average, and daily profiles may deviate substantially from it. A researcher may choose to determine the actual profile on a given day by use of pibal balloon observations. However, this approach would prove to be an uneconomic use of time and money. The more economic approach would be to use the Gaussian model with a constant wind speed assumption and realize that the concentrations may be overestimated at downwind distances in excess of approximately 2 Km depending upon the stability conditions and the actual wind speed profile.

## C. General Comments on the Use of the Gaussian Model:

This thesis has described the use of the Gaussian model in an actual control strategy evaluation problem and some of the problems encountered. This type of project should not be considered as the only use of the Gaussian model. Despite its simplicity, the Gaussian model may serve as a useful tool to locate key sampling sites after a source has been put into operation. Using the Star Data, which give the frequency of wind speeds and directions under various stability conditions, the model can be applied to locate areas where concentrations are expected to be at or above standard levels. It can also be used to locate areas where concentrations are above the detection thresholds of the sampling devices. Such applications will have to eventually be made for the Pine Bluff mill to assure compliance with ADPCE standards.

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# APPENDIX A

## NOMENCLATURE

| | |
|---|---|
| $\tilde{C}$ | pollutant concentration |
| $\tilde{C}$ | normalized ground level concentration |

$$\tilde{C} = \frac{U \quad c(x,\ o,\ o)}{S}$$

| | |
|---|---|
| $\tilde{C}_I$ | normalized concentration with a non-infinite inversion height |
| $\tilde{C}_U'$ | normalized concentration with an infinite inversion height |
| $\tilde{C}_B$ | normalized concentration computed using Briggs' plume height (rise) equations |
| $\tilde{C}_H$ | normalized concentration computed using Holland's plume rise equation |
| $\tilde{C}_{10}$ | normalized concentration assuming that the wind speed at z = 10 m is constant throughout the mixing layer |
| $\tilde{C}_{HS}$ | normalized concentration using the wind speed computed for the top of the stack using the power law (Eq. 13) |
| $\tilde{C}_{AD}$ | normalized concentration computed using the wind speed averaged through the plume |
| $D_S$ | inside stack diameter |
| F | buoyancy flux |
| $F_A$ | atmospheric stability coefficient |

| | |
|---|---|
| $g$ | gravitational acceleration |
| $H$ | plume centerline height (effective stack height) |
| $H_S$ | stack height |
| $\Delta H$ | plume rise above the stack top |
| $L$ | inversion height |
| $n$ | exponent of the wind speed power law profile |
| $P_A$ | ambient pressure |
| $Q(X, t \mid X_0, t_0)$ | transition probability density for movement from location $X_0$ at time $t_0$ to location X at time t |
| $R$ | ratio of the plume height to the inversion height |
| $S$ | source emission rate |
| $S_A$ | atmospheric stability parameter |
| St | atmospheric stability class |
| $t$ | time |
| $T_A$ | ambient temperature |
| $T_S$ | temperature of the gas exiting from the stack |
| $U$ | mean wind speed in the horizontal direction |
| $U_Z$ | mean wind speed at height Z |
| $U_1$ | mean wind speed at height $Z_1$ |
| $U_{10}$ | mean wind speed at Z = 10 m |
| $V_S$ | gas exit velocity |
| W.D. | wind direction (0° is north, 90° is east) |
| W.S. | wind speed |
| $X$ | position vector |
| $x$ | distance component in the horizontal mean wind velocity direction |

| | |
|---|---|
| $x^*$ | distance at which the turbulence becomes the dominant parameter influencing plume rise |
| $x_m$ | downwind distance from the source to the point of maximum plume rise |
| $x_I'$ | downwind distance from the recovery stack along the receptor string I |
| $y$ | distance component in the horizontal crosswind direction ($y = 0$ is the plume concentration centerline) |
| $z$ | distance component in the vertical direction ($z = o$ is the ground level) |
| $\sigma_y$ | standard deviation distance of the plume concentration distribution in the crosswind direction |
| $\sigma_z$ | standard deviation distance of the plume concentration distribution in the vertical direction |
| $\langle\ \rangle$ | time averaged quantity |
| Subscripts | I, II, III, IV, V - receptor string numbers |

# APPENDIX B

## GAUSSIAN MODEL PROGRAM

```
C MPSGCM
C  MPSGCM IS A MODIFIED VERSION OF UNAMAP (NTIS) PROGRAM
C  PTMTP
C  IT ALLOWS THE USER TO CONSIDER A CHANGE IN WIND SPEED
C  WITH HEIGHT.
C
C MPSGCM CALLS SUBROUTINES BEH072, NEWRCX, AND ADPLHT
C NEWRCX CALLS DBTSIG AND NEWSIG
C ADPLHT CALLS PLUME AND DBTSIG
C PLUME CALLS NEXTU
C
C FORM OF INPUT TO MPSGCM
C
C  VARIABLE   COLUMNS   FORMAT   VARIABLE DESCRIPTION
C
C CARD TYPE 1 (1 CARD) * * * TITLE CARD * * *
C  . ALP        1-80       40A2      JOB TITLE
C
C CARD TYPE 2 (1 CARD) * * * CONTROL CARD * * *
C
C   KTR1       1           I1,1X      =1 PRINT PARTIAL
C                                        CONCENTRATIONS
C                                     =2 DOES NOT
C   KTR2       3           I1         =1 ADJUSTS WIND SPEED
C                                     =2 DOES NOT
C
C CARD TYPE 3 (UP TO 31 CARDS, LAST ONE BLANK FOR CONTROL)
C    * * * SOURCE CARD * * *
C   QS         1-9         F9.1       EMISSION RATE (G/SEC)
C   HS         10-18       F9.1       STACK HEIGHT (M)
C   TS         19-27       F9.1       GAS TEMPERATURE (DEG K)
C   VS         28-36       F9.1       GAS EXIT VELOCITY (M/SEC)
C   DS         37-45       F9.1       INSIDE STACK DIAMETER (M)
C   RS         46-54       F9.3       R COORDINATE OF STACK (KM)
C   SS         55-63       F9.3       S COORDINATE OF STACK (KM)
C
C CARD TYPE 4 (UP TO 31 CARDS, LAST ONE BLANK FOR CONTROL)
C    * * * RECEPTOR CARD * * *
C
C   RR         1-9         F9.4       R COORDINATE (KM)
C   SR         10-18       F9.4       S COORDINATE (KM)
C   ZR         19-27       F9.4       HEIGHT ABOVE GROUND (M)
C
C CARD TYPE 5 (ANY NUMBER OF CARDS, LAST ONE BLANK FOR CONTROL)
C    * * * METEOROLOGY CARD * * *
C
C   THETA      1-9         F9.1       WIND DIRECTION (DEG)
C   U          10-18       F9.1       WIND SPEED (M/SEC)
C   IST        19          I1,1X      STABILITY CLASS
C   HL         21-29       F9.1       MIXING HEIGHT (M)
C   TA         30-38       F9.1       AMBIENT SURFACE TEMPERATURE
C                                     (DEG K)
C        TA IS DEFAULTED TO 293 DEG K.
C   PA         39-47       F9.1       AMBIENT SURFACE PRESSURE (MB)
C        PA IS DEFAULTED TO 960 MB.
C
      DIMENSION ALP(40),QS(31),HS(31),TS(31),VS(31),DS(31),RS(31),
     1RR(31),SR(31),ZR(31),TCON(31),PCON(31,31),HFS(30),XFS(30),NR(30),
     2DCON(10),SS(31)
C POWER LAWS ARE ASSUMED FOR U
C  EXPONENTS OF THE POWER LAWS ARE ENTERED BY STABILITY CLASS
C  PERKINS' VALUES BEING USED
C
      COMMON A(6)
      DATA A/0.25,0.29,0.33,0.38,0.44,0.50/
C
C READ AND WRITE NUMBERS
      IR=5
      IW=6
C OPEN INPUT AND OUTPUT FILES
      CALL SEARCH(1,'DATAIN',1,0)
      CALL SEARCH(2,'DATAOT',2,0)
C MAXIMUM NUMBERS OF SOURCES AND RECEPTORS
      MAX =30
C READ CARD TYPE 1, TITLE ********************************************
      READ(IR,10)(ALP(I),I=1,40)
   10 FORMAT(40A2)
      WRITE(IW,10)(ALP(I),I=1,40)
C READ CARD TYPE 2, CONTROL ****************************************
      READ(IR,20)KTR1,KTR2
   20 FORMAT(2(I1,1X))
C WRITE HEADING FOR PRINTOUT OF SOURCE INFORMATION
```

```
   30 FORMAT(/)
   40 FORMAT(//)
   50 FORMAT(///)
      WRITE(IW,60)
   60 FORMAT('SOURCES')
      WRITE(IW,70)
   70 FORMAT('NO.',5X,'EM. RATE',2X,'HEIGHT',2X,'TEMP.',2X,'VELOC.',
     12X,'DIAM.')
C READ CARD TYPE 3, SOURCE ******************************************
      MAXP1=MAX+1
      DO 80 I=1,MAXP1
      J=I
      READ(IR,90)QS(I),HS(I),TS(I),VS(I),DS(I),RS(I),SS(I)
   90 FORMAT(5F9.1,2F9.3)
      IF(QS(I))100,100,80
   80 CONTINUE
      WRITE(IW,110)MAX
  110 FORMAT('NUMBER OF SOURCES HAS EXCEEDED ',I2)
      WRITE(IW,120)
  120 FORMAT('RESET VALUES IN DIMENSION AND TRY AGAIN')
      GO TO 999
C NUMBER OF SOURCES
  100 ISOR=J-1
C WRITE SOURCE INFORMATION
      DO 130 I=1,ISOR
      WRITE(IW,140)I,QS(I),HS(I),TS(I),VS(I),DS(I)
  140 FORMAT(I2,6X,F6.1,2X,F6.1,2X,F5.1,2(2X,F6.1))
      WRITE(IW,30)
  130 CONTINUE
      WRITE(IW,150)
  150 FORMAT('NO.',8X,'R',11X,'S')
      DO 160 I=1,ISOR
      WRITE(IW,170)I,RS(I),SS(I)
  170 FORMAT(I2,2(5X,F7.3))
      WRITE(IW,30)
  160 CONTINUE
C WRITE HEADING FOR RECEPTOR LOCATION PRINTOUT
      WRITE(IW,180)
  180 FORMAT('RECEPTORS')
      WRITE(IW,190)
  190 FORMAT('NO.',7X,'R(KM)',9X,'S(KM)',9X,'Z(KM)')
C READ CARD TYPE 4, RECEPTOR ****************************************
      DO 200 I=1,MAXP1
      J=I
      READ(IR,210)RR(I),SR(I),ZR(I)
  210 FORMAT(3F9.4)
C IF BLANK CARD IS ENCOUNTERED GO TO NEXT SECTION
      IF(RR(I)*RR(I)+SR(I)*SR(I))220,220,200
  200 CONTINUE
      WRITE(IW,230)MAX
  230 FORMAT('NUMBER OF RECEPTORS HAS EXCEEDED ',I2)
      WRITE(IW,120)
      GO TO 999
C NUMBER OF RECEPTORS
  220 IREC=J-1
C WRITE RECEPTOR LOCATIONS
      DO 240 I=1,IREC
      WRITE(IW,250)I,RR(I),SR(I),ZR(I)
  250 FORMAT(I2,3(5X,F9.4))
      WRITE(IW,30)
  240 CONTINUE
C READ CARD TYPE 5, METEOROLOGY *************************************
  260 READ(IR,270)THETA,U,IST,HL,T,P
  270 FORMAT(2F9.1,I1,1X,3F9.1)
C IF IST IS ZERO OR NEGATIVE GO TO PROGRAM END
      IF(IST)999,999,280
C WRITE METEOROLOGY HEADING
  280 WRITE(IW,290)
  290 FORMAT('METEOROLOGY')
      WRITE(IW,300)
  300 FORMAT(2X,'THETA',11X,'U',8X,'IST',7X,'HL',13X,'T',13X,'P')
      WRITE(IW,310)THETA,U,IST,HL,T,P
  310 FORMAT(2(F9.1,5X),I1,5X,3(F9.1,5X))
C THETA IN RADIANS
      TDUM=THETA*0.0174533
      SINT=SIN(TDUM)
      COST=COS(TDUM)
```

```
C D(THETA)/DZ IS INITIALLY ASSUMED TO BE ZERO
      DTHDZ=0.
C ZERO CONCENTRATION MEMORY LOCATIONS
      DO 320 J=1,IREC
      TCON(J)=0.
      DO 320 I=1,ISOR
  320 PCON(I,J)=0.
C CALCULATE CONCENTRATIONS FOR EACH SOURCE
      DO 330 IS=1,ISOR
C ROUTING CONSTANT
      K=1
      HP=HS(IS)
      TP=TS(IS)
      VP=VS(IS)
      DP=DS(IS)
      VF=0.
      HFS(IS)=9999.
C CALCULATE CONCENTRATIONS AT EACH RECEPTOR SITE
      DO 330 IRC=1,IREC
C RELATIVE COORDINATES
      R=RS(IS)-RR(IRC)
      S=SS(IS)-SR(IRC)
C DOWNWIND DISTANCE
      X=S*COST+R*SINT
C IF X IS ZERO OR NEGATIVE GO TO NEXT RECEPTOR OR SOURCE
      IF(X)330,330,340
C CROSSWIND DISTANCE
  340 Y=S*SINT-R *COST
C CALL PLUME HEIGHT ROUTINE IF NEW SOURCE
      GO TO (350,360),K
C ESTIMATE HEIGHT USING BRIGGS' METHOD
  350 GO TO (380,370),KTR2
C PLUME HEIGHT ESTIMATION ASSUMING CONSTANT WIND SPEED
  370 CALL BEH072(HF,HX,HMW,F,DELH,DISTF,DELHX,HP,TP,VP,DP,VF,
     1IST,U,X,DTHDZ,T,P)
      GO TO 390
  380 CALL ADPLHT(HF,HX,DISTF,HP,TP,VP,DP,IST,U,X,
     1DTHDZ,T,P)
  390 K=2
      HFS(IS)=HF
      XFS(IS)=DISTF
      IF(X-DISTF)400,400,410
  400 H=HX
      GO TO 420
  410 H=HF
      GO TO 420
  360 IF(X-XFS(IS))430,440,440
  440 H=HFS(IS)
      GO TO 420
  430 GO TO (460,450),KTR2
  450 CALL BEH072(HF,HX,HMW,F,DELH,DISTF,DELHX,HP,TP,VP,DP,VF,IST,U,
     1X,DTHDZ,T,P)
      GO TO 470
  460 CALL ADPLHT(HF,HX,DISTF,HP,TP,VP,DP,IST,U,X,
     1DTHDZ,T,P)
  470 H=HX
C COMPUTE RELATIVE CONCENTRATION
  420 ZL=ZR(IRC)
      CALL NEWRCX(U,ZL,H,HL,X,Y,IST,KTR2,RC)
      PCON(IS,IRC)=RC*QS(IS)
      TCON(IRC)=TCON(IRC)+PCON(IS,IRC)
  330 CONTINUE
C CONCENTRATIONS IN MICROGRAMS/M**3
      DO 480 J=1,IREC
      TCON(J)=TCON(J)*1.0E+06
      DO 480 I=1,ISOR
  480 PCON(I,J)=PCON(I,J)*1.0E+06
C WRITE OUTPUT TABLE
      N1=0
      DO 490 J=1,IREC
      IF(TCON(J)-1.)490,500,500
  500 N1=N1+1
      NR(N1)=J
  490 CONTINUE
      N2=1
      N3=5
  510 IF(N1-N2)260,530,540
  540 IF(N1-N3)550,550,560
  550 N4=N1
      GO TO 570
  560 N4=N3
```

```
 570 WRITE(IW,580)
 580 FORMAT(59X,'RECEPTORS')
     WRITE(IW,590)(NR(I),I=N2,N4)
 590 FORMAT(22X,5(I2,16X))
     WRITE(IW,30)
     GO TO (600,610),KTR1
 600 WRITE(IW,620)
 620 FORMAT('SOURCE  FINAL HGT  PARTIAL CONC. (MICROGR/M**3)',/)
     DO 630 I=1,ISOR
     L=1
     DO 640 JR=N2,N4
     J=NR(JR)
     DCON(L)=PCON(I,J)
 640 L=L+1
     L=L-1
     WRITE(IW,650)I,HFS(I),(DCON(L2),L2=1,L)
 650 FORMAT(2X,I2,5X,F6.1,4X,5(E8.2,9X))
 630 CONTINUE
     WRITE(IW,30)
 610 WRITE(IW,660)
 660 FORMAT(19X,'TOTAL CONC. (MICROGR/M**3)',/)
     L=1
     DO 670 JR=N2,N4
     J=NR(JR)
     DCON(L)=TCON(J)
 670 L=L+1
     L=L-1
     WRITE(IW,680)(DCON(L2),L2=1,L)
 680 FORMAT(19X,5(E8.2,9X))
     WRITE(IW,50)
     N2=N2+5
     N3=N3+5
     GO TO 510
 530 J=NR(N1)
     WRITE(IW,845)J
 845 FORMAT(22X,I2)
     GO TO (690,700),KTR1
 690 J=NR(N1)
     WRITE(IW,620)
     DO 710 I=1,ISOR
     WRITE(IW,720)I,HFS(I),PCON(I,J)
 720 FORMAT(2X,I2,5X,F6.1,4X,E8.2)
 710 CONTINUE
     WRITE(IW,30)
 700 WRITE(IW,660)
     WRITE(IW,730)TCON(J)
 730 FORMAT(19X,E8.2)
     WRITE(IW,50)
     GO TO 260
 999 CALL SEARCH(4,'DATAIN',0,0)
     CALL SEARCH(4,'DATAOT',0,0)
     CALL EXIT
     END
C ****NEWRCX***************************************************************
     SUBROUTINE NEWRCX(U,Z,H,HL,X,Y,IST,K,RC)
C THIS IS A MODIFIED VERSION OF TURNER'S UNAMAP SUBROUTINE DBTRCX
C
C IF THE PLUME IS ABOVE THE LID SET RC=0. AND RETURN
     IF(H-HL)10,10,20
C IF THE RECEPTOR IS ABOVE THE LID, RC=0. AND RETURN
  10 IF(Z-HL)30,30,20
  20 RC=0.
     RETURN
C IF X IS LESS THAN 1 METER, RC=0. AND RETURN
  30 IF(X-0.001)20,40,40
C CALL DBTSIG TO OBTAIN SIGMA-Y AND Z
  40 CALL DBTSIG(X,X,IST,SY,SZ)
C DUMMY VARIABLE FOR WIND SPEED
     UU=U
C IF HEIGHT EFFECTS ARE TO BE CONSIDERED, CALL NEWSIG
     GO TO (50,55),K
  50 CALL NEWSIG(U,SZ,IST,H,UN)
     UU=UN
C DUMMY VARIABLE
  55 C1=1.
     IF(Y)60,70,60
C Y IN METERS
  60 YM=1000.*Y
C FOR NONZERO Y
     YEXP=0.5*(YM/SY)**2
```

```
C IF YEXP IS LARGER THAN 50., RC=0. AND RETURN
      IF(YEXP-50.)80,20,20
   80 C1=EXP(YEXP)
C IF STABLE OR UNLIMITTED MIXING HEIGHT, USE WADE EQUATIONS
   70 IF(IST-4)90,90,100
   90 IF(HL-5000.)110,100,100
  100 C2=2.*SZ**2
      IF(Z)20,120,130
  120 C3=H*H/C2
C IF C3 IS GREATER THAN 50., RC=0. AND RETURN
      IF(C3-50.)140,20,20
  140 A2=1./EXP(C3)
C WADE EQUATION FOR A GROUND LEVEL RECEPTOR
      RC=A2/(3.14159*UU*SY*SZ*C1)
      RETURN
  130 A2=0.
      A3=0.
      CA=Z-H
      CB=Z+H
      C3=CA*CA/C2
      C4=CB*CB/C2
      IF(C3-50.)150,160,160
  150 A2=1./EXP(C3)
  160 IF(C4-50.)170,180,180
  170 A3=1./EXP(C4)
C WADE EQUATION FOR ELEVATED RECEPTOR
  180 RC=(A2+A3)/(6.28318*UU*SY*SZ*C1)
      RETURN
C IF SIGMA-Z IS GREATER THAN 1.6 TIMES THE MIXING HEIGHT, THE
C  DISTRIBUTION BELOW THE LID IS UNIFORM WITH HEIGHT REGARDLESS OF
C  PLUME HEIGHT
  110 IF((SZ/HL)-1.6)190,190,200
C WADE EQUATION
  200 RC=1./(2.5066*UU*SY*HL*C1)
      RETURN
C COUNTER
  190 AN=0.
      IF(Z)20,210,220
  220 A1=1./(6.28318*UU*SY*SZ*C1)
      C2=2.*SZ**2
      A2=0.
      A3=0.
      CA=Z-H
      CB=Z+H
      C3=CA*CA/C2
      C4=CB*CB/C2
      IF(C3-50.)230,240,240
  230 A2=1./EXP(C3)
  240 IF(C4-50.)250,260,260
  250 A3=1./EXP(C4)
  260 SUM=0.
      THL=2.*HL
  270 AN=AN+1.
      A4=0.
      A5=0
      A6=0.
      A7=0.
      C5=AN*THL
      CC=CA-C5
      CD=CB-C5
      CE=CA+C5
      CF=CB+C5
      C6=CC*CC/C2
      C7=CD*CD/C2
      C8=CE*CE/C2
      C9=CF*CF/C2
      IF(C6-50.)280,290,290
  280 A4=1./EXP(C6)
  290 IF(C7-50.)300,310,310
  300 A5=1./EXP(C7)
  310 IF(C8-50.)320,330,330
  320 A6=1./EXP(C8)
  330 IF(C9-50.)340,350,350
  340 A7=1./EXP(C9)
  350 T=A4+A5+A6+A7
      SUM=SUM+T
      IF(T-0.01)360,270,270
  360 RC=A1*(A2+A3+SUM)
      RETURN
  210 A1=1./(6.28318*UU*SY*SZ*C1)
      A2=0.
```

```
      C2=2.*SZ**2
      C3=H*H/C2
      IF(C3-50.)370,380,380
  370 A2=2./EXP(C3)
  380 SUM=0.
      THL=2.*HL
  390 AN=AN+1.
      A4=0.
      A6=0.
      C5=AN*THL
      CC=H-C5
      CE=H+C5
      C6=CC*CC/C2
      C8=CE*CE/C2
      IF(C6-50.)400,410,410
  400 A4=2./EXP(C6)
  410 IF(C8-50.)420,430,430
  420 A6=2./EXP(C8)
  430 T=A4+A6
      SUM=SUM+T
      IF(T-0.01)440,390,390
  440 RC=A1*(A2+SUM)
      RETURN
      END
C ***** NEWSIG ***************************************************************
      SUBROUTINE NEWSIG(U,SZ,IST,H,UN)
      COMMON A(6)
C HERE THE VALUE OF U ENTERED BY THE USER AND SZ ARE ASSUMED TO APPLY
C  AT Z=10M . IF THIS HEIGHT IS INAPPROPRIATE , CHANGES SHOULD BE
C  MADE IN THE VALUE BELOW
      Z0=10.
      AP1=A(IST)+1.
      A1=1./AP1
      ZA=Z0**A(IST)
C BASE HEIGHT OF THE PLUME
      C1=H-2.*SZ
C TOP HEIGHT OF THE PLUME
      C2=H+2.*SZ
      IF(C1)10,10,20
C ENTIRE PLUME ABOVE GROUND LEVEL
   20 F=(C2**AP1-C1**AP1)*A1/(4.*SZ*ZA)
      GO TO 30
C BOTTOM OF PLUME BELOW GROUND LEVEL
   10 F=(C2**AP1)*A1/(C2*ZA)
C NEW U
   30 UN=U*F
      RETURN
      END
C **** ADPLHT ****************************************************************
      SUBROUTINE ADPLHT(HF,HX,XF,HS,TS,VS,DS,IST,U,X,DTH,T,P)
      COMMON A(6)
C HEIGHT AT WHICH INPUT U AND SIGMA-Z ARE ASSUMED TO APPLY
      Z0=10.
C DEFAULT T AND P IF REQUIRED
      IF(T)10,10,20
   10 T=293.
   20 IF(P)30,30,40
   30 P=960.
C VOLUME FLOW RATE FROM STACK
   40 VF=0.785398*VS*DS**2
C BUOYANCY FLUX
      F=3.12139*VF*(TS-T)/TS
C IF D(THETA)/DZ IS ZERO DEFAULT IT TO APPROPRIATE VALUES
      IF(DTH)50,50,60
   50 GO TO(60,60,60,60,70,80),IST
   70 DTH=0.02
      GO TO 60
   80 DTH=0.035
C STABILITY PARAMETER
   60 S=9.80616*DTH/T
C GO TO STABILITY ORIENTED AREAS
      GO TO (90,90,90,90,100,100),IST
C UNSTABLE AND NEUTRAL CONDITIONS
   90 IF(F-55.)110,120,120
C DISTANCE AT WHICH TURBULENCE DOMINATES
  110 XST=14.*F**0.625
      GO TO 130
  120 XST=34.*F**0.4
C DOWNWIND DISTANCE TO FINAL PLUME RISE
  130 XF=3.5*XST
      XFM=XF/1000.
```

```
      CALL DBTSIG(XFM,XFM,IST,SY,SZF)
C CONTROL PARAMETER
      I=1
C CALL PLUME HEIGHT ROUTINE TO DETERMINE FINAL PLUME HEIGHT
      CALL PLUME(XF,SZF,U,Z0,F,S,HS,I,IST,HF)
C X IN METERS
      XM=1000.*X
C IF X=0., CALCULATE FINAL PLUME HEIGHT ONLY
      IF(X)140,140,150
  140 HX=0.
      GO TO 160
C SIGMA-Z AT XM
  150 CALL DBTSIG(X,X,IST,SY,SZ)
      I=1
      CALL PLUME(XM,SZ,U,Z0,F,S,HS,I,IST,HX)
      IF(HF-HX)170,160,160
  170 HX=HF
      GO TO 160
C STABLE CONDITIONS
C
C DOWNWIND DISTANCE TO FINAL PLUME RISE UNDER STABLE CONDITIONS
C  IS COMPUTED USING WIND SPEED AT THE TOP OF THE STACK.
C
  100 UHS=U*(HS/Z0)**A(IST)
      XF=3.14159*UHS/SQRT(S)
      XFM=XF/1000.
C TURNER'S FINAL PLUME HEIGHT
      HFT=5.*(F**0.25)/S**0.375
C SZ AT XF
      CALL DBTSIG(XFM,XFM,IST,SY,SZF)
      I=2
      CALL PLUME(XF,SZF,U,Z0,F,S,HS,I,IST,HF)
      IF(HF-HFT)180,180,190
  190 HF=HFT
  180 IF(X)140,140,200
  200 XM=1000.0*X
      IF(XM-XF)150,150,210
  210 HX=HF
  160 XF=XF/1000.
      RETURN
      END
C ****** PLUME ************************************************************
      SUBROUTINE PLUME(X,SZ,U,Z0,F,S,HS,I,IST,HP)
      F1=1.6*F**0.333333
      X1=X**0.666667
C FIRST GUESS AT PLUME HEIGHT
      GO TO (10,20),I
   10 DH=F1*X1/U
      GO TO 30
   20 F2=2.4*(F/S)**0.333333
      DH=F2/(U**0.333333)
   30 DH1=DH
   35 HP1=HS+DH
C NEW GUESS AT WIND SPEED
   40 CALL HEXTU(U,DH,HP1,HS,SZ,Z0,IST,UH)
C NEW GUES AT PLUME HEIGHT
      GO TO (50,60),I
   50 DH2=F1*X1/UH
      GO TO 70
   60 DH2=F2/(UH**0.333333)
   70 HP2=HS+DH2
      DELH=ABS(HP1-HP2)
      IF(DH1-DELH)80,80,90
   90 FRAC=DELH/HP1
      IF(FRAC-0.01)100,100,110
  110 DH=DH2
      DH1=DELH
      GO TO 35
   80 HP=HP1
      GO TO 120
  100 HP=HP2
  120 RETURN
      END
C ***** HEXTU *************************************************************
      SUBROUTINE HEXTU(U,DH,HP,HS,SZ,Z0,IST,UH)
      COMMON A(6)
      C1=Z0**A(IST)
      C2=1.+A(IST)
```

```
      C3=1./C2
      H1=DH+2.*SZ
      H2=(HP+2.*SZ)**C2
      H3=HS**C2
      UN=U*C3*(H2-H3)/(H1*C1)
      RETURN
      END
      SUBROUTINE BEH072   (HF,HX,HMW,F,DELHF,DISTF,DELHX,HP,TS,VS,D,VF,
     1 KST,U,X,DTHDZ,T,P)
C        BEH072   (BRIGGS EFFECTIVE HEIGHT)    OCTOBER 1972
C        D. B  TURNER, RESEARCH METEOROLOGIST* MODEL APPLICATIONS BRANCH
C         METEOROLOGY LABORATORY, ENVIRONMENTAL PROTECTION AGENCY.
C           ROOM 3168, NCHS BUILDING, RTP. PHONE (919) 549-8411 EXT 4564
C        MAILING ADDRESS: MTL,EPA, RESEARCH TRIANGLE PARK, NC 27711.
C         * ON ASSIGNMENT FROM NATIONAL OCEANIC AND ATMOSPHERIC
C              ADMINISTRATION, DEPARTMENT OF COMMERCE.
C         THIS DIFFERS FROM THE AUGUST 1972 VERSION IN STATEMENT 24 + 1:
C          THE CONSTANT 2.4 PREVIOUSLY WAS 2.9, AND IN STATEMENT 27:
C          THE CONSTANT 3.14159 PREVIOUSLY WAS 2.4
C        THIS VERSION OF BRIGGS EFFECTIVE HEIGHT TO CALCULATE PLUME RISE
C         FROM A SINGLE SOURCE IS BASED ON:
C           1) BRIGGS,GARY A., 1971: SOME RECENT ANALYSES OF PLUME RISE
C                OBSERVATION. PP 1029 - 1032 IN PROCEEDINGS OF THE SECOND
C                INTERNATIONAL CLEAN AIR CONGRESS, EDITED BY H. M. ENGLUN
C                AND W. T. BEERY. ACADEMIC PRESS, NEW YORK.
C           2) BRIGGS, GARY A.,1972: DISCUSSION ON CHIMNEY PLUMES IN
C                NEUTRAL AND STABLE SURROUNDINGS. ATMOS. ENVIRON. 6, 507
C              - 510. (JUL 72).
C         OUTPUT VARIABLES ARE...
C           HF     FINAL EFFECTIVE PLUME HEIGHT (METERS)
C           HX     EFFECTIVE PLUME HEIGHT FOR DISTANCE X (METERS)
C           HMW    HEAT OUTPUT OF SOURCE (MW)
C           F      BUOYANCY FLUX (M**4/SEC**3)
C           DELHF FINAL PLUME RISE (METERS)
C           DISTF DISTANCE OF FINAL PLUME RISE FROM SOURCE (KM)
C           DELHX PLUME RISE AT DISTANCE X (METERS)
C         INPUT VARIABLES ARE...
C           HP     PHYSICAL STACK HEIGHT (METERS)
C           TS     STACK GAS TEMPERATURE (DEG K)
C           VS     STACK GAS EXIT VELOCITY (M/SEC)
C           D      INSIDE STACK DIAMETER (METERS)
C           VF     STACK GAS VOLUMETRIC FLOW RATE (M**3/SEC)
C           KST    STABILITY (CLASS), SEE PAGE 209 OF PASQUILL,
C                   ATMOSPHERIC DISPERSION.  CLASSES DEFINED BY...
C                     1 IS PASQUILL STABILITY CLASS A
C                     2 IS PASQUILL STABILITY CLASS B
C                     3 IS PASQUILL STABILITY CLASS C
C                     4 IS PASQUILL STABILITY CLASS D
C                     5 IS PASQUILL STABILITY CLASS E
C                     6 IS PASQUILL STABILITY CLASS F
C           U      WIND SPEED (M/SEC)
C           X      DOWNWIND DISTANCE (KM)
C           DTHDZ POTENTIAL TEMPERATURE LAPSE RATE (DEG K/METER)
C           T      AMBIENT AIR TEMPERATURE (DEG K)
C           P      AMBIENT AIR PRESSURE (MB)
C        THANKS TO DALE COVENTRY FOR HIS HELPFUL DISCUSSION ON
C         PROGRAMMING PLUME RISE, TO ROGER THOMPSON FOR THE COMMENT
C         CARDS, AND TO RUSS LEE WHO REVISED THIS ACCORDING TO REFERENCE
      IF(T)1,1,2
C        T = 0. MEANS NO AMBIENT TEMPERATURE GIVEN.  USE T = 293.
    1 T = 293.
    2 IF(P)3,3,4
C        P = 0  MEANS NO AMBIENT AIR PRESSURE GIVEN.  USE P = 960.
    3 P = 960.
C        IF VF IS NOT GIVEN, CALCULATE IT FROM STACK DATA.
    4 IF(VF)5,5,6
    5 VF = 0.785398*VS*D*D
C        THE CONSTANT 0.785398 = PI/4
    6 F = 3.12139*VF*(TS-T)/TS
C        THE CONSTANT 3.12139 IS THE ACCELERATION DUE TO GRAVITY / PI.
      HMW = 0.00011217*F*P
C        THE CONSTANT 0.00011217 = PI TIMES THE SPECIFIC HEAT OF AIR AT
C         CONSTANT PRESSURE (0.24 CAL/GM*DEG K) TIMES MOLECULAR WEIGHT
C         OF AIR (28.966 GM/GM MOLE) DIVIDED BY IDEAL GAS CONSTANT
C         (0.0831 MB*M**3/GM.MOLE*DEG K) AND ACCELERATION DUE TO GRAVITY
C         (9.80616 M/SEC*SEC) AND THEN MULTIPLIED BY (4.1855E-06 MW/CAL
C         PER SEC) TO CONVERT THE ANSWER TO MEGAWATTS.
C        GO TO APPROPRIATE BRANCH FOR STABILITY CONDITION GIVEN.
C        IF UNSTABLE OR NEUTRAL GO TO 7, IF STABLE GO TO 20.
      GO TO (7,7,7,7,20,20,20),KST
```

```
C         DETERMINE APPROPRIATE FORMULA FOR CALCULATING XST, DISTANCE AT
C          WHICH TURBULENCE BEGINS TO DOMINATE.  THE FORMULA USED DEPENDS
C          UPON BUOYANCY FLUX. STATEMENTS 8 AND 9 ARE EQUATION (7).
7      IF(F-55.)8,9,9
8      XST=14.*F**.625
       GO TO 10
9      XST=34.*F**.4
10     DISTF=3.5*XST
       DELHF=1.6*F**0.333333*DISTF**0.666667/U
       IF(X)29,29,32
C         IF X = 0.0, CALCULATE FINAL RISE ONLY, IF X IS GREATER THAN
C          0.0, CALCULATE RISE FOR DISTANCE = X ALSO.
    32 XM = 1000.* X
C         XM IS X IN METERS.
C         STATEMENT 14 IS EQUATION (6), REFERENCE 1.
    14 DELHX = 1.6*F**0.333333*XM**0.666667/U
       IF(DELHX.GT.DELHF)DELHX=DELHF
       GO TO 30
    20 IF(DTHDZ)21,21,24
C         IF DTHDZ IS NEGATIVE OR ZERO ASSIGN TO IT A VALUE OF 0.02 OR
C          0.035 IF STABILITY IS SLIGHTLY STABLE OR STABLE, RESPECTIVELY.
    21 GO TO (7,7,7,7,22,23,23),KST
    22 DTHDZ = 0.02
       GO TO 24
    23 DTHDZ = 0.035
    24 S = 9.80616*DTHDZ/T
C         THE CONSTANT 9.80616 IS THE ACCELERATION DUE TO GRAVITY.
C         S IS A STABILITY PARAMETER.
C         CALCULATE PLUME RISE ACCORDING TO EQUATION (4), REFERENCE 1.
       DHA = 2.4*(F/(U*S))**0.333333
C         CALCULATE PLUME RISE BY EQUATION (5), REFERENCE 1 FOR LIGHT
C          WIND CONDITIONS ACCORDING TO MORTON, TAYLOR, AND TURNER.
       DELHF = 5.0*F**0.25/S**0.375
       IF(DHA-DELHF) 25,25,27
    25 DELHF = DHA
C         DISTANCE TO FINAL PLUME RISE IS GIVEN BY THE FOLLOWING
    27 DISTF = 3.14159*U/S**0.5
C         IF X = 0.0, CALCULATE FINAL RISE ONLY, IF X IS GREATER THAN
C          0.0, CALCULATE RISE FOR DISTANCE = X ALSO.
C         IF X IS ZERO OR LESS, GO TO 29 AND SET PLUME RISE AND DIST. TO
C          MAXIMUM PLUME RISE EQUAL TO ZERO.
       IF(X)29,29,33
    33 XM = 1000.*X
C         XM IS X IN METERS.
C         IF XM IS GREATER THAN THE DISTANCE TO THE POINT OF FINAL PLUME
C          RISE, SET PLUME RISE EQUAL TO FINAL PLUME RISE, OTHERWISE,
C          CALCULATE PLUME RISE FROM EQUATION (6),REFERENCE 1.
       IF(XM-DISTF)14,14,28
    28 DELHX = DELHF
       GO TO 30
    29 DELHX = 0.
       HX = 0.
       GO TO 31
C         CALCULATE EFFECTIVE HEIGHT AT DISTANCE X.
    30 HX = HP + DELHX
C         CALCULATE FINAL EFFECTIVE HEIGHT.
    31 HF = HP + DELHF
       DISTF = DISTF/1000.
       RETURN
       END
       SUBROUTINE DBTSIG (X,XY,KST,SY,SZ)
       DIMENSION XA(7),XB(2),XD(5),XE(8),XF(9),AA(8),BA(8),AB(3),BB(3),
      1 AD(6),BD(6),AE(9),BE(9),AF(10),BF(10)
       DATA XA/.5,.4,.3,.25,.2,.15,.1/
       DATA XB/.4,.2/
       DATA XD /30.,10.,3.,1.,.3/
       DATA XE /40.,20.,10.,4.,2.,1.,.3,.1/
       DATA XF /60.,30.,15.,7.,3.,2.,1.,.7,.2/
       DATA AA /453.85,346.75,258.89,217.41,179.52,170.22,158.08,122.8/
       DATA BA /2.1166,1.7283,1.4094,1.2644,1.1262,1.0932,1.0542,.9447/
       DATA AB /109.30,98.483,90.673/
       DATA BB /1.0971,0.98332,0.93198/
       DATA AD /44.053,36.650,33.504,32.093,32.093,34.459/
       DATA BD /0.51179,0.56589,0.60486,0.64403,0.81066,0.86974/
       DATA AE /47.618,35.420,26.970,24.703,22.534,21.628,21.628,23.331,
      1 24.26/
       DATA BE /0.29592,0.37615,0.46713,0.50527,0.57154,0.63077,0.75660,
      1 0.81956,0.8366/
```

```
      DATA AF /34.219,27.074,22.651,17.836,16.187,14.823,13.953,13.953,
     1 14.457,15.209/
      DATA BF /0.21716,0.27436,0.32681,0.41507,0.46490,0.54503,0.63227,
     1 0.68465,0 78407,0 81558/
      GO TO (10,20,30,40,50,60),KST
C          STABILITY A (10)
   10 TH = (24.167 - 2.5334*ALOG(XY))/57.2958
      IF (X.GT.3.11) GO TO 69
      DO 11 ID = 1,7
      IF(X.GE.XA(ID)) GO TO 12
   11 CONTINUE
      ID = 8
   12 SZ = AA(ID) * X ** BA(ID)
      GO TO 71
C          STABILITY B (20)
   20 TH = (18.333 - 1.8096*ALOG(XY))/57.2958
      IF(X.GT.35.) GO TO 69
      DO 21 ID = 1,2
      IF (X.GE.XB(ID)) GO TO 22
   21 CONTINUE
      ID = 3
   22 SZ = AB(ID) * X ** BB(ID)
      GO TO 70
C          STABILITY C (30)
   30 TH = (12.5 - 1.0857*ALOG(XY))/57.2958
      SZ = 61.141 *X ** 0.91465
      GO TO 70
C          STABILITY D (40)
   40 TH = (8.3333-0.72382*ALOG(XY))/57.2958
      DO 41 ID = 1,5
      IF (X.GE.XD(ID)) GO TO 42
   41 CONTINUE
      ID = 6
   42 SZ = AD(ID) * X ** BD(ID)
      GO TO 70
C          STABILITY E (50)
   50 TH = (6.25 - 0.54287*ALOG(XY))/57 2958
      DO 51 ID = 1,8
      IF (X.GE.XE(ID)) GO TO 52
   51 CONTINUE
      ID = 9
   52 SZ = AE(ID) * X ** BE(ID)
      GO TO 70
C          STABILITY F (60)
   60 TH = (4.1667 - 0.36191*ALOG(XY))/57.2958
      DO 61 ID = 1,9
      IF (X.GE.XF(ID)) GO TO 62
   61 CONTINUE
      ID = 10
   62 SZ = AF(ID) * X ** BF(ID)
      GO TO 70
   69 SZ = 5000.
      GO TO 71
   70 IF (SZ.GT.5000.) SZ = 5000.
   71 SY = 1000. * XY * SIN(TH)/(2.15 * COS(TH))
      RETURN
      END
```

# APPENDIX C

## SUPPLEMENTAL GRAPHS

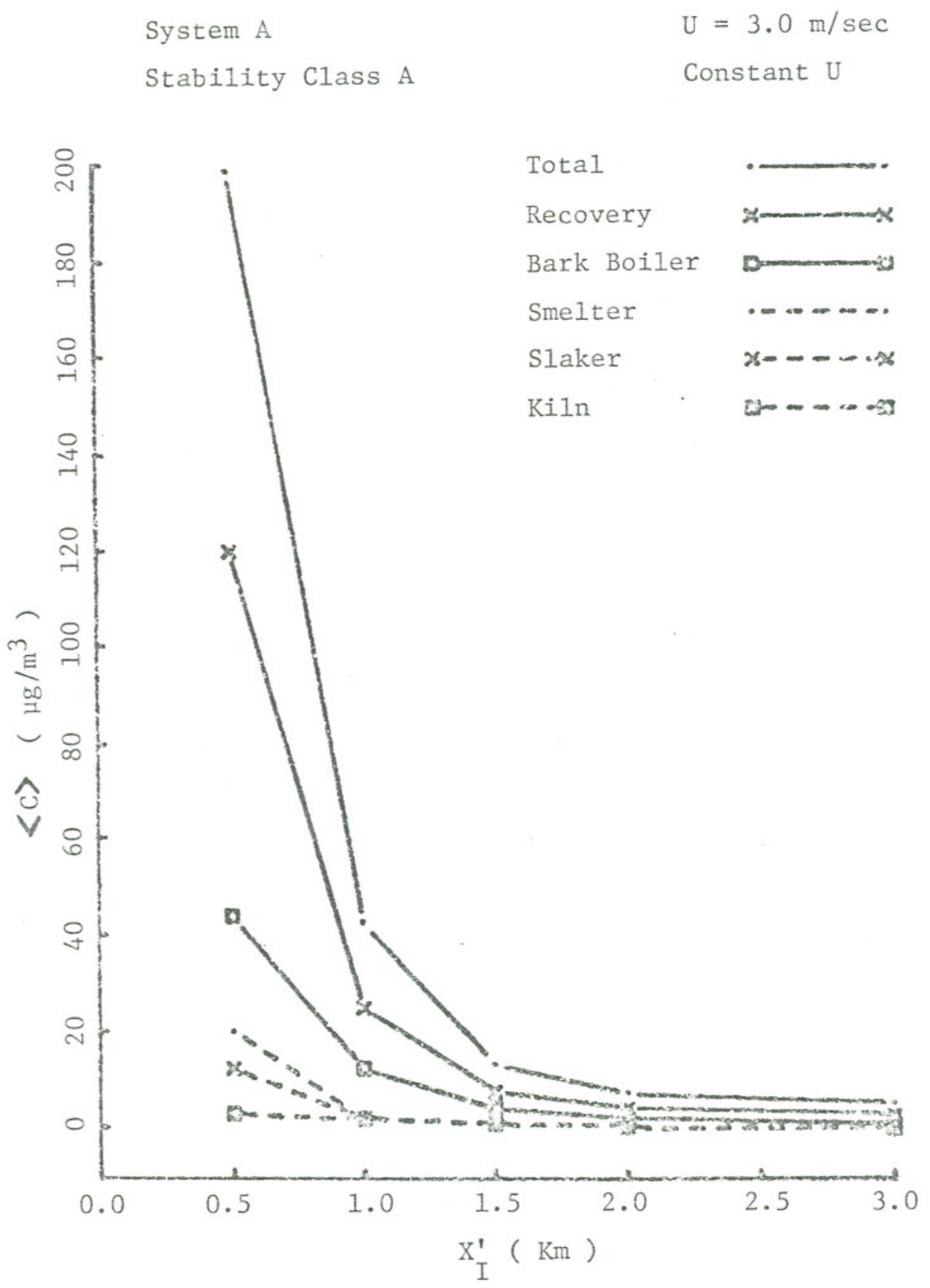


Figure C1. Ground level concentration versus distance along receptor string I.

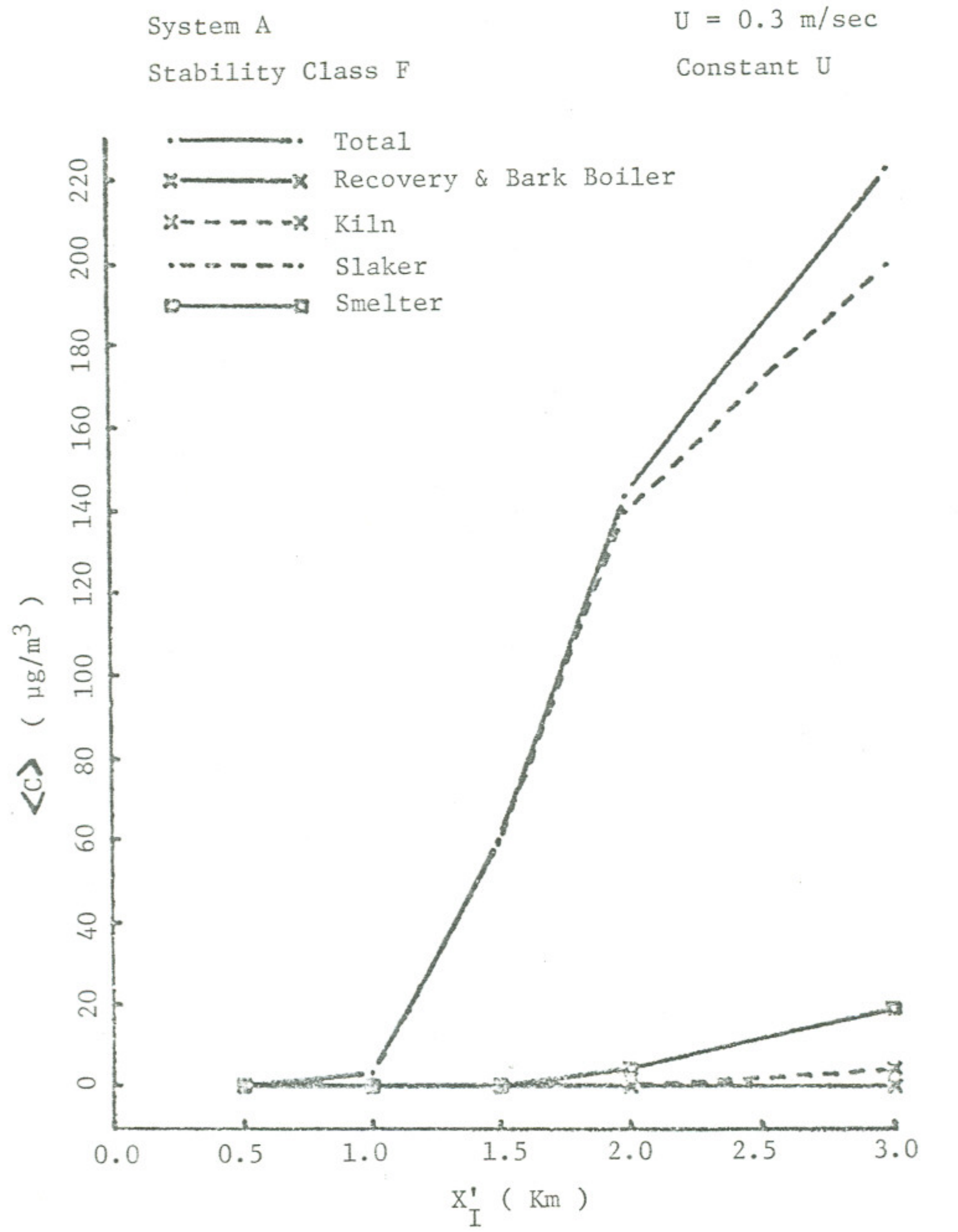


Figure C2. Ground level concentration versus distance along receptor string I.

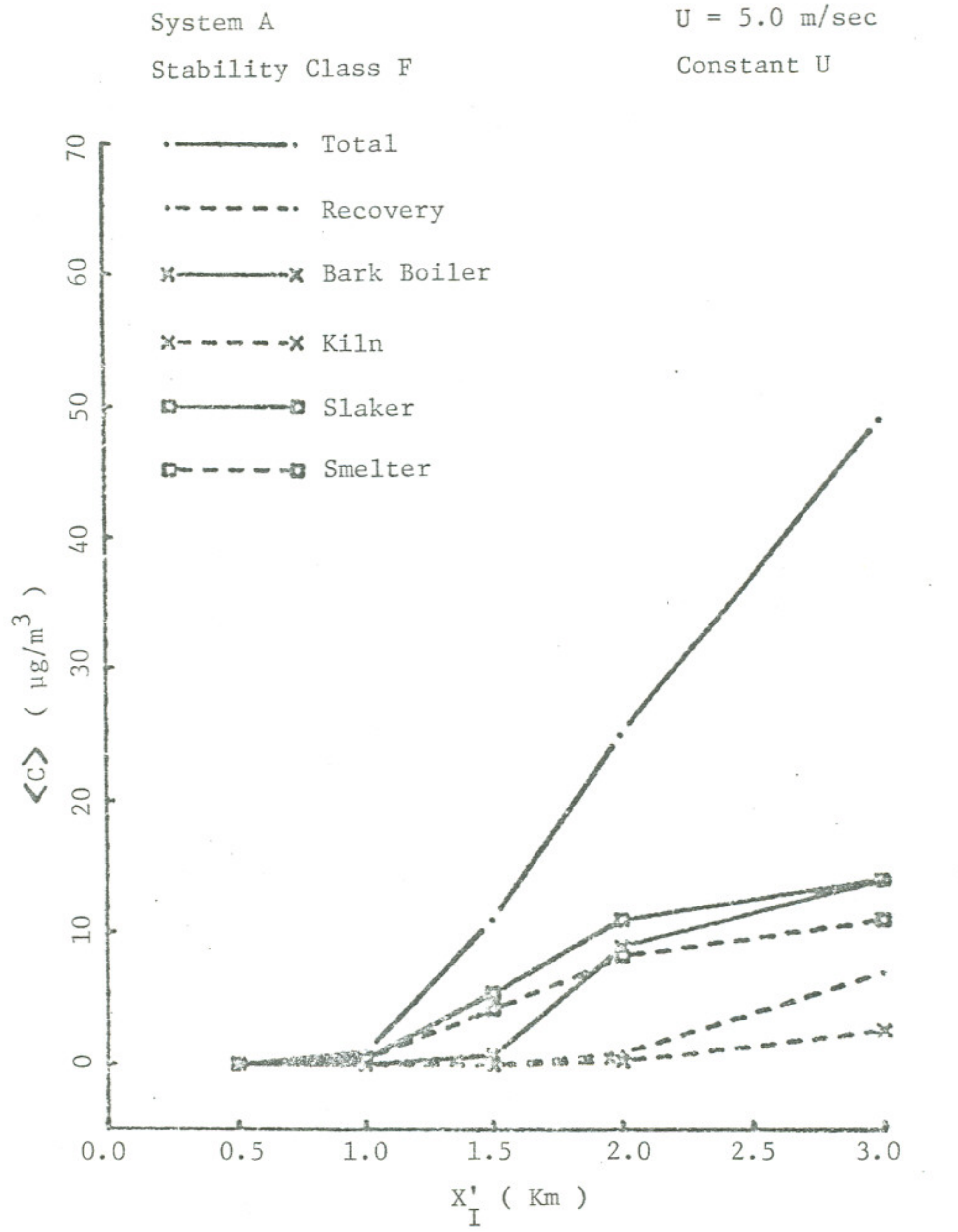


Figure C3. Ground level concentration versus distance along receptor string I.


Figure C4. Ground level concentration versus distance along receptor string I.

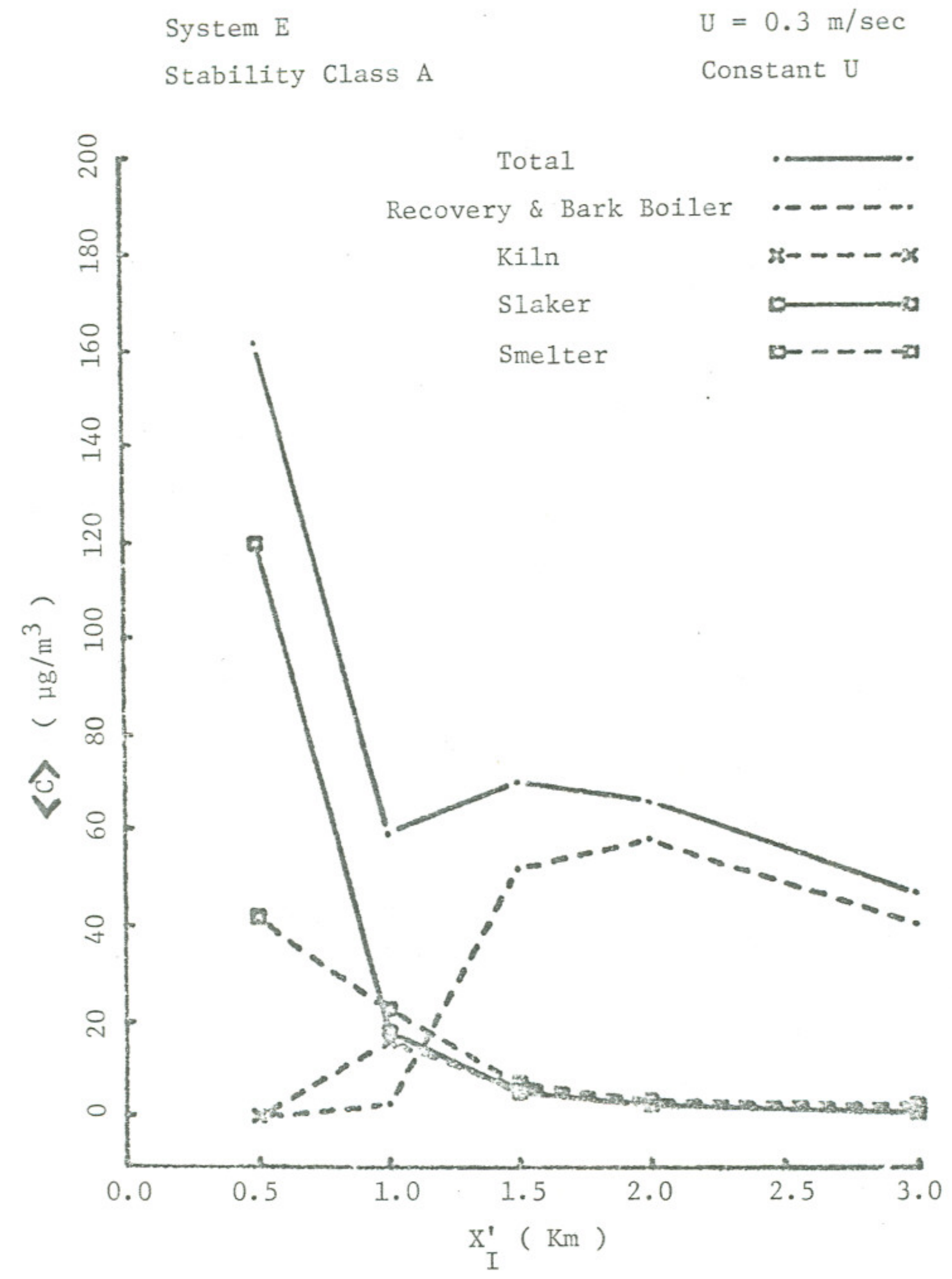


Figure C5. Ground level concentration versus distance along receptor string I.

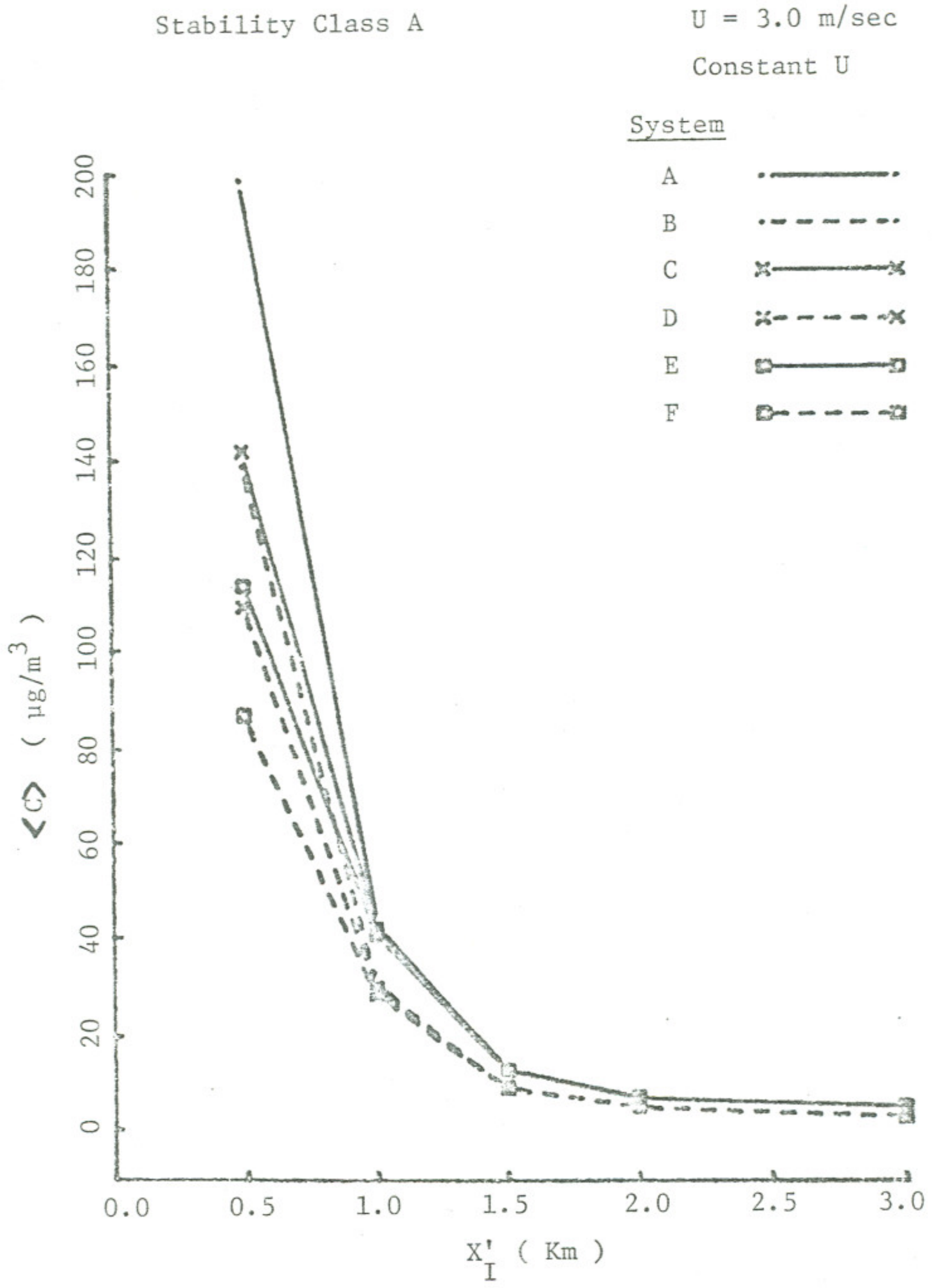


Figure C6. Ground level concentration versus distance along receptor string I for all control strategies.

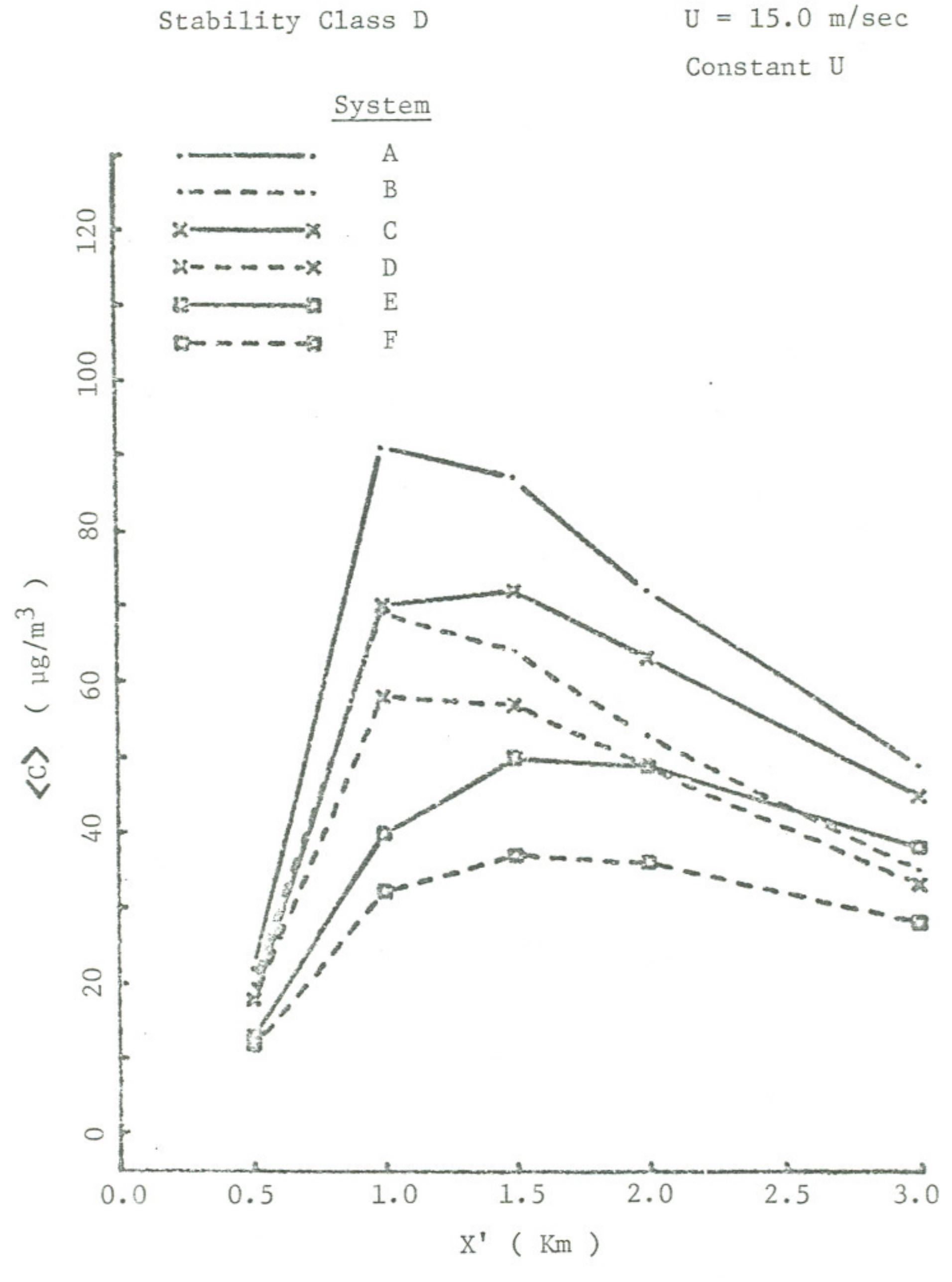


Figure C7. Ground level concentration versus distance along receptor string I for all control strategies.

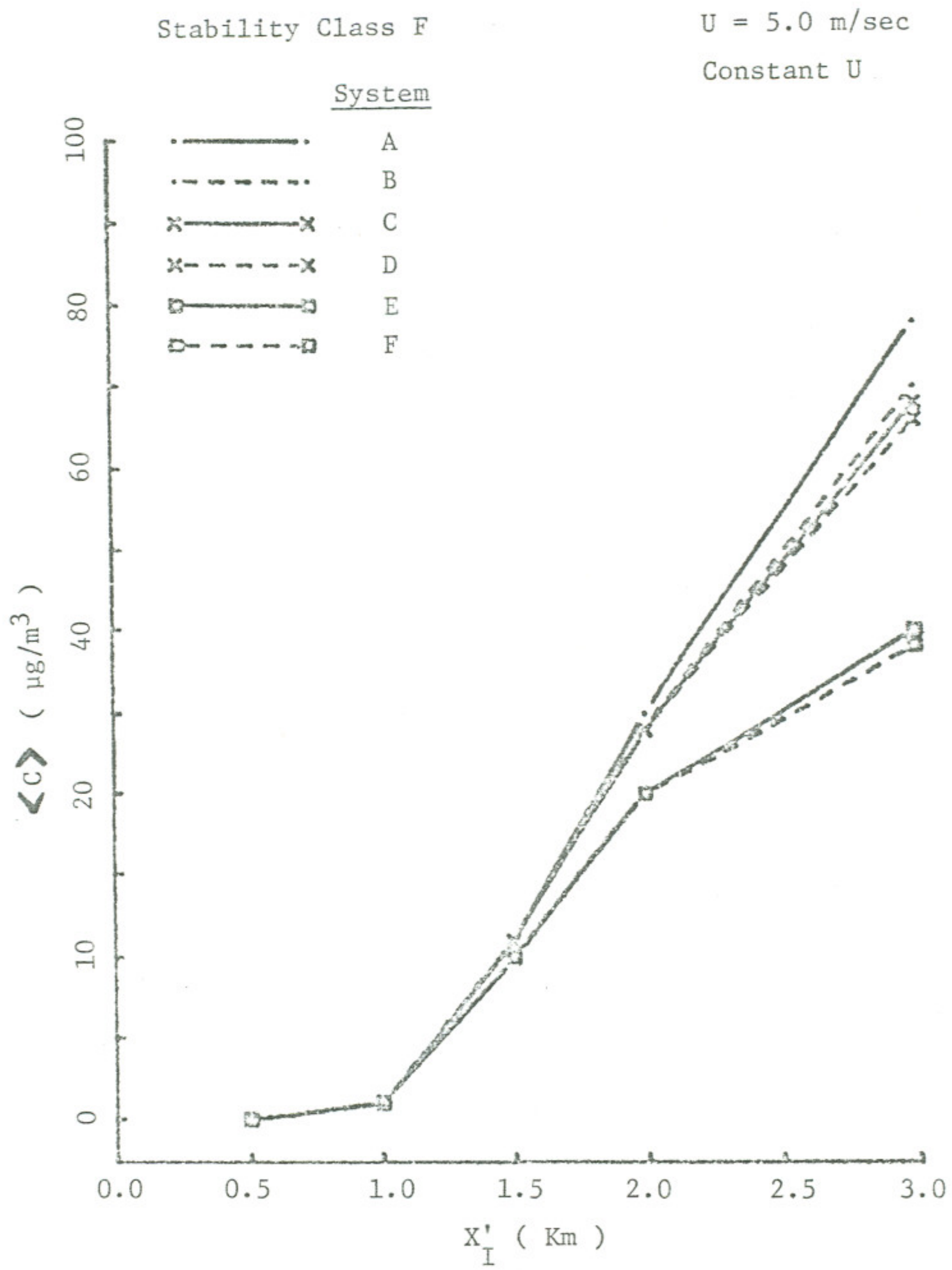


Figure C8. Ground level concentration versus distance along receptor string I for all control strategies.

# VITA

The author was born in Ionia, Michigan on June 21, 1949. His public school education was obtained in Saranac, Michigan, where he graduated in 1967. He then attended Central Michigan University and graduated in December, 1971 with a Bachelor of Science degree in Physics. The author then attended the University of Toledo and graduated in June, 1975 with a Master of Science degree in Physics and Astronomy. In February, 1975 he began his graduate studies at the Oregon Graduate Center. Working under the guidance of Dr. Richard L. Pitter, the requirements for a Master of Science degree in Environmental Technology were completed in July, 1977.